Enabling Sustainable Thinking in Undergraduate Engineering Education*

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In this paper we address the need for curricular changes that foster sustainable thinking and review a number of engineering curricular changes at selected universities, drawing comparisons to medical and other fields. For each engineering program, we examined the level at which sustainability concepts and active-learning methods were integrated into its curricula. A majority of the universities examined "bolted-on" various components of sustainability or student-centered learning into their existing programs. Only one university examined has made significant efforts to redesign engineering education in terms of sustainability and pedagogy. A number of barriers hindering the re-orientation of engineering curricula toward "sustainable" engineering are discussed.

Keywords: sustainability; problem-based learning; intellectual development

INTRODUCTION

OVER THE LAST 30 years, the concepts of "sustainability" and "sustainable development" have been introduced in order to address the causes and effects of humanity's increasing impact on the world. Sustainability can be defined as "design of human and industrial systems to ensure that humankind's use of natural resources and cycles does not lead to diminished quality of life due either to losses in further economic opportunities or to adverse impacts on social conditions, human health and the environment" [1]. Inherent in the notion of sustainability is the interaction and connection between society, the environment, and economic/industrial development. In order to achieve sustainable development among both industrialized and developing countries, the interrelationships between these three "pillars" of sustainability must be realized. However, no such balance can be achieved without an adequate understanding of how societal and industrial actions impact the environment in which we live or how today's activities may impact future generations. As a result, there is considerable need for increased knowledge and awareness of the issues surrounding sustainable development.

A profession central to resource use and development is engineering. With the pressures of rising population and declining resources, engineers will be called upon to design more eco-efficient systems and technologies, to deal with ever-increasing uncertainty, and to consider the social and economic impacts of engineering choices in both a national and global setting [2]. In order for future engineers to participate in sustainable design and manufacturing, they will be required to evaluate and apply information from multiple disciplines, such as economics, public policy, and the environmental and social sciences. In addition, sustainable development is surrounded by uncertainty and ambiguity. The modern engineer needs to be equipped with the knowledge and skills to manage this uncertainty and make judgments about the best course of action based on the available evidence. This requires engineers of the 21st century to have creative problem-solving skills and to "evaluate the implications of their solutions beyond their immediate technical context" [3]. However, critical thinking skills and the ability to collect, evaluate, and utilize information are often not advanced in current engineering graduates. They also have little or no experience of dealing with uncertainty and ambiguity in problem-solving. Too often, engineering curricula place more emphasis on the memorization of facts and well-established procedures than on learning the skills necessary to deal with large, complex problems. As a result, current engineering graduates are entering the market place ill-equipped to deal with the problems society is sure to face.

The United Nations established the global need for a reorientation of education at the Earth Summit in Rio de Janeiro in 1992 [4]. One of the results of this conference was the document known as Agenda 21, which emphasized the importance of

effective teaching methods. In addition, at the World Summit on Sustainable Development in Johannesburg in 2002, the UN identified the need to reform existing education policies, programs, and practices so that they foster the concepts, skills, motivation, and commitment needed for sustainable development [5]. The UN's new vision of education includes "linking social, economic, political, and environmental concerns," which "demands a deeper, more ambitious way of thinking about education, one that retains a commitment to critical analysis while fostering creativity and innovation." Although there has been clear evidence of support for education reform to better prepare engineering students for confronting sustainability issues, relatively little has been done, due to the lack of incentive within universities and the barriers of the status quo that must be overcome.

Successful integration of sustainability principles and methods into engineering curricula requires a systemic change in our approach to education and societal values. Students not only need the knowledge base to make sound engineering decisions, they need the intellectual development (e.g. higher-level cognitive and critical thinking skills) to supply effective solutions to complex technical problems. Wise et al. [6] conducted a four-year longitudinal study of intellectual development in engineering undergraduates. Their results indicate that, without active-learning and team-based projects, students fail to progress adequately in terms of intellectual growth. In turn, they often lack the critical thinking skills, confidence, and creativity needed to successfully evaluate the impact of corporate decisions on the environment and society.

Although there is great need for engineering education reform, social and economic factors influence the motivation and ability of universities to evolve beyond the status quo. Therefore, a better understanding of the incentives and barriers to change is needed. In this paper we review a number of engineering curricular changes that selected universities have made, drawing comparisons with medical and other fields. For each engineering program, we examined the level at which sustainability concepts and active-learning methods were integrated into the curricula. Based on our analysis, factors that may promote successful curricular development were identified. Of specific interest was the identification of characteristics that enable engineering curricula to be redesigned for sustainability. Because moving towards sustainability requires open-mindedness and collaboration with a broad range of stakeholders, including industry, government, students, and educators, a top-down approach to reform may not work. Therefore, incorporating sustainability into higher education requires a new "vision of possibilities" and an evolution in our way of thinking. Part 2 of this series of papers [7] introduces one such vision—a case study where both sustainability and student-centered learning become integral components in a multi-disciplinary course on sustainability indicators.

INTELLECTUAL DEVELOPMENT

Intellectual development or growth is described as the "progression from ignorant certainty to intelligent confusion" [8]. Empirical work by Perry [9] indicates that intellectual development takes place in distinct stages which are characterized by a student's perception of truth. According to Perry's model, students progress through several levels of intellectual development ranging from blind acceptance to contextual relativism [9]. The Perry model laid the groundwork for many other models of intellectual development [10–12]. These models generally follow Perry's, but they modify his model, illuminating differences in learning and behavior patterns between genders. Although men and women may exhibit different learning patterns in the early stages of intellectual development, the learning behavior of individuals at the highest levels of intellectual development are the same for both genders.

In the first levels of intellectual development students believe that all knowledge is certain and that their responsibility as students is to accept, without question, the answers given to them by authorities [8, 9]. This dualistic approach to learning assumes that scholastic and moral questions have only one correct answer. As students progress in their intellectual growth, they recognize that not all knowledge is certain and take increasing responsibility for constructing their own judgments. They become less reliant on authority for support in their beliefs or personal feelings, and eventually take full responsibility for their own learning. At the highest stages for growth, students recognize that all knowledge is contextual and individually constructed. Therefore, they use the best available information (e.g. intuition, objective analysis, their own thoughts, thoughts of others) to make judgments and decisions in the face of ambiguity and uncertainty [8, 9]. As summarized by Felder and Brent [8], individuals at the highest level of intellectual development:

1. possess the skepticism and inclination to challenge what is currently known;
2. question the assumptions underlying all accepted wisdom;
3. are reluctant to accept the first reasonable explanation;
4. employ both logic and intuition; and
5. avoid transferring judgments made in one situation to another situation without critical evaluation.

The five attributes described above could be used to define an exceptional scientist or engineer. They also describe the skills needed by professionals to design for a more sustainable world. The most

appropriate (e.g. the most sustainable) solution to a problem is not necessarily a technical improvement. Roy Sutherland [13] describes an apt scenario solidifying this point:

> A number of complaints were lodged stating that the elevator in a multi-story building was too slow. The manager solicited bids from engineering firms to increase the elevator's speed. Most of the bids came in above $300,000, however one firm offered a $5,000 solution. The engineers at this firm presented a creative alternative to more costly technological upgrades. They proposed installing floor to ceiling mirrors, on each floor, outside of the elevator doors. With little to lose, the managers select the non-technical solution. The complaints stopped. Preoccupied by grooming and observing others, people were no longer bothered by the time spent waiting for the elevator.

This example of creative innovation and simplicity underscores the need for engineers to understand the social (and other) dimensions of their work. However, the insight to move away from more traditional avenues of problem-solving are not a trait of lower levels of intellectual development. Understanding the different intellectual stages and the ways to encourage progression between them is a prerequisite for helping students attain the creativity they need to function effectively as engineering professionals [8] in the 21st century. However, many engineering courses tend to support a "dualistic" mode of learning by emphasizing facts and well-established principles and procedures [14]. It is not until later in the senior or graduate years that students become introduced to more complex, ambiguous problems through case studies, research, and design experience. Thus, most students enter college operating at the dualism level and leave at a level far short of "contextual knowing" as described above [8].

Relation to sustainability

The successful application of sustainability principles and ideas in the engineering profession requires that engineers are capable (and willing) to critically assess the implications of their professional actions. More importantly, it requires that engineers have the skills to supply creative solutions to complex problems in the face of ambiguity and oftentimes conflicting goals. We cannot realistically integrate sustainability into engineering education in the hopes of cultivating these problem-solving skills without adequately addressing the issue of intellectual development. Therefore, the integration of sustainability concepts into engineering curricula needs to occur with the concomitant facilitation of intellectual growth and development.

There is research to suggest a positive correlation between intellectual development and other growth aspects, such as multicultural awareness, moral reasoning, and acceptance of diversity [15]. If fostering higher intellectual development can promote greater social and cultural awareness among individuals, it too may support more

sustainable thinking. By developing critical thinking in engineering students, the next generation of professionals may be more likely to give consideration to issues (e.g. the environment, social equity, biodiversity) that they otherwise would have ignored.

Promoting intellectual development

To promote intellectual development and creative thinking (prerequisites for sustainable thinking), instructors should employ pedagogy that encourages a deep approach to learning facilitated by a variety of learning tasks, clear communication of expectations, constructive feedback, mutual respect, and a student-centered learning environment [16]. One of the most defining characteristics of intellectual growth is a decrease in reliance on instructors to provide the answers to questions. In order to foster student independence and self-reliance, instructional methods that encourage self-directed learning are needed. Student-centered learning refers to removal of the instructor as the primary source of information. Students are given the responsibility for their own learning and the instructor takes on the role of a facilitator or guide in that learning process. This is a significant departure from lecture-based instruction. Student-centered learning can be promoted using active, cooperative, and/or inductive learning. An instructional method that incorporates all three of these learning processes is problem-based learning (PBL). PBL is an approach to education in which students are presented with complex, ill-defined problems in order to develop problem-solving skills and stimulate learning [17]. The following section provides a more detailed discussion of PBL and other methods for incorporating sustainability concepts and promoting intellectual development in engineering students.

ENHANCING LEARNING IN ENGINEERING CURRICULA

Sterling's [18] discussion of the ways sustainability can be incorporated into higher education mirrors the concept of intellectual development discussed above. An academic institution can respond to the call for sustainability on a number of levels, from superficial to systemic. A first-level response is characterized by a lack of response and could be caused by ignorance or denial of the current issue of sustainability. Accommodation within curriculum and minimal institutional change mark a second-level response. In this case, sustainability concepts are "bolted-on" to the existing system. At the third level, the system itself is reformed, sustainability becomes "built-in" to the system, and the dominant educational paradigm is modified. Sterling identifies the fourth level of response as "a redesign on sustainability principles, based on a realization of the need for paradigm change. This type of response emphas-

Fig. 1. The degree of sustainability integration into curriculum and thought in higher education.

izes the process and the quality of learning, which is seen as an essentially creative, reflexive and participative process." This relationship between the level of response pursued in higher education (i.e. none, bolted-on, built-in, redesign), and the level of integration of sustainability into both thought and curriculum is summarized in Fig. 1.

Learning environment

The educational paradigm that Sterling advocates is, essentially, learner-centered environments. Learner-centered education seeks to improve the quality of learning by promoting discovery and the construction of knowledge [19]. This requires a redefinition of the learning environment, the roles of instructors, the roles of learners and of the relationship among them. In the learner-centered environment, students and faculty jointly construct knowledge and collaboration between students and faculty is fostered within and across courses, disciplines, and departments. Problem-solving, communication, and self-expression are all tools used to promote learning.

In learner-centered environments, the purpose of the relationships between students and instructors is to promote deep learning in students. Power is shared in the classroom and the students are actively involved in determining course content, assessment methods, and policies. An instructor might give students a choice between a selection of assessment methods or work with students to establish expectations for outcomes and behavior in the course. Furthermore, personal relationships between students and faculty promote positive expectations and participation [20–21].

The primary contribution of the instructor is "creating and maintaining conditions that promote student growth and movement toward autonomy" [22]. To this end, instructors should aim to develop every student's competencies and talents using

varied teaching approaches which address multiple learning styles and aspects of intelligence [19].

Students accept responsibility for their learning, which has psychological importance because: (1) learning is most effective when it is an intentional process of constructing meaning from information and experience and (2) intrinsic motivation is stimulated by new and difficult tasks that have a relevance to personal interests [23]. As students connect new knowledge to old, applying and organizing information in a way that is meaningful to them, they develop intellectually. "This not only results in a deeper understanding—it creates autonomous, independent learners" [24]. Those that seek to develop solutions to sustainability issues must have the capacity to collaborate with people from all walks of life. They must possess the ability to examine problems from a global perspective with an understanding of the connectivity between all things.

Problem-based learning

One of the most successful student-centered learning tools is problem-based learning (PBL). PBL is the "learning that results from the process of working toward the understanding or resolution of a problem" [25]. The application of PBL in higher education (as we know it today) originated in the 1960s and 1970s as a means to rethink the way we prepare future physicians for professional practice [26]. The faculty members of McMaster University in Canada led the way in developing a problem-based curriculum as an alternative to the traditional approaches used for teaching basic science and clinical skills to medical students [27]. PBL was their attempt to improve the retention, application skills, and overall learning of medical students. McMaster's successful implementation of PBL ignited the acceptance and integration of PBL into the curriculum at other medical institutions throughout Europe, Australia, and the United States. Since its first applications, PBL has spread to auxiliary medical disciplines and other fields such as business, law, education, police science, and engineering [28].

Medical professionals are routinely confronted with complex problems that require analytical and clinical reasoning skills. In addition, medical professionals are constantly faced with new types of problems, as well as new information about existing problems. There is an old educational truism that states "half of what the students learn in medical school will be wrong or outdated by the time they are in practice, and no one knows which half that is" [29]. This means that medical students must be comfortable taking ownership of their education so that they can become effective and efficient life-long learners. The use of PBL in medical education uses "real-world" problems as stimuli for learning. In addition, these problems help to integrate and organize learned information in ways that will improve recollection and application of knowledge to future problems. The need for this type of learning is not unique to medical education. Considering the problem-solving nature of the engineering profession and the complex, ill-defined nature of many issues surrounding sustainability, PBL is a necessary tool to prepare future engineers for the workplace.

In order to maximize PBL's potential, the Southern Illinois School of Medicine Problem Based Learning Initiative (PBLI), established the following essential elements for problem-based learning [28].

1. Students must take responsibility for their own learning.
2. Problems should be ill-defined and allow for free inquiry by the student.
3. Problems must be multidisciplinary.
4. Student collaboration should be encouraged in both group- and self-directed work.
5. Students must constantly re-analyze problems as individuals and as a group.
6. Students must reflect on what they have learned from the problem.
7. Students must take part in self and peer assessment.
8. Problems must have value in the real world.
9. Student assessments must evaluate problem-solving skills.
10. PBL must be rooted in the curriculum, not episodic.

Therefore, PBL is much more than students working through problems. A more accurate definition of PBL might be "student-centered, problem-based, inquiry-based, integrated, collaborative, re-iterative learning" [29]. In Table 1 we have outlined the PBL methods and approaches for selected universities and programs within the United States and Canada that are incorporating PBL into some or all of their undergraduate programs. The educational goals of the institutions vary, along with the level of PBL integration and the instructional or learning methods used. Speculation as to the reasoning behind these differences is presented later in this paper in the "Incentives and Barriers to Change" section.

INCORPORATING PROBLEM-BASED LEARNING IN ENGINEERING EDUCATION TO FOSTER SUSTAINABILITY

Transformation of educational systems to support sustainable thought equates to a redesign of engineering curricula. The question then becomes, not how can we improve the current education system, but how can we create a more effective and efficient educational system. We examined a number of accredited engineering programs to determine the level of PBL and sustainability integration within their curricula (Table 2). Sterling's [18] response levels of higher education to sustainability and education—bolted-on, built-in, and redesign—were used. In this paper

Table 1. Problem-based learning goals and approach for selected universities

School	Goals	Approach
McMaster University; School of Medicine[a]	For students to acquire and put into practice concepts and information required to understand and manage health care problems. To promote critical thinking, clinical, and self-directed learning skills.	The central focus of program is the tutorial. In the tutorial sessions, small groups of students work together to solve problems and to negotiate their approach to learning tasks. The faculty at McMaster pioneered the use of PBL in medical education. PBL is used throughout the three-year curriculum.
Southern Illinois University; School of Medicine & Physicians Assistant Program[b]	Promote self-directed learning through problem simulations that are ill-structured and allow for free inquiry. Encourage collaboration, self and peer assessment, and continual opportunities to learn.	Curriculum uses patient formats and standardized patients to facilitate student inquiry and problem solving. Integrates learning with other disciplines to improve understanding and treatment of patient problems. Created the Problem Based Learning Initiative (PBLI) which is a group of instructors and researchers active in PBL research and faculty educational development.
University of Delaware; Biology, Biochemistry, Chemistry, Science, Physics & Nutrition[c]	Enhance student's critical thinking, communication, research and life-long learning skills. Promote intellectual, emotional, physical, social, and spiritual development of students and teachers.	Student-centered, active learning techniques that focus on group-based projects. Use of peer tutors and a variety of learning experiences. University has created the Institute for Transforming Undergraduate Education to promote reform of undergraduate education through faculty development and course design.
Ohio University; Business Administration[d]	To develop communication, collaboration, and teamwork skills. Program also strives to develop personal characteristics such as initiative, creativity, and personal responsibility.	Use of projects, involving macro-problems that require a holistic view of business. Access to information is based on the "just-in-time" concept, where students are provided information at a time when it is the most useful. Most projects are in collaborative learning groups.
Smith College; Picker Engineering Program[e]	To apply the current knowledge of cognitive development to a learner-centered pedagogy that is present throughout the curriculum of the Engineering Department.	Use of concept maps and reflective narratives, as well as hands-on, inquiry based, group based work or problems. Require a year-long capstone course where seniors collaborate in teams on real-world projects sponsored by industry and government. New program. First engineering program at all female university.
McMaster University; School of Engineering (Chemical Engineering)[f]	Develop student's lifetime learning skills so that they can more effectively and efficiently acquire knowledge in the future. Promote the development of process and problem-solving skills.	Use of PBL in courses at the sophomore, junior and senior level. Require students to participate in a workshop on team building and teamwork before undergoing PBL exercises. Use of tutorless groups, facilitated by student and instructor feedback. Developed the McMaster Problem Solving Program that includes strategies, assessment, and guidance for faculty to use PBL in courses.
Carnegie Mellon; School of Engineering[g]	To develop courses that promote a smooth transition between the acquisition of factual knowledge and the application of this knowledge to problems in a decision-making framework.	The use of concept maps and open-ended decision-making exercises where students are required to define the problem, suggest alternatives, and make decisions. The course development at Carnegie Mellon was part of an NSF Foundation Course and Curriculum Development Grant. Therefore, the actual integration of these courses into the schools curriculum is uncertain.
Michigan Technological University; School of Engineering[h]	To help students discover knowledge. To encourage innovation, inquiry, and learning through the hands-on application of knowledge to solve problems significant to industry. To promote teamwork among students and with faculty.	Students can earn credit by participating in the Enterprise Program; a program which gives teams of students the opportunity to solve engineering, manufacturing, and design problems supplied by industry partners. Teams include freshman to senior level students. Purdue University has a similar program called EPICS.

[a] Barrow (1966); McMaster School of Medicine website: <http://www.fhs.mcmaster.ca/mdprog/overview/overview.htm>
[b] Southern Illinois University School of Medicine and PBLI websites: <http://edaff.siumed.edu/> & <http://www.pbli.org/>
[c] University of Delaware website: <http://www.udel.edu/pbl/>
[d] Stinson and Milter (1996); Ohio University School of Business website: <http://www.cob.ohiou.edu/policies/missionstatement.asp>
[e] Grasso et al. (2004); Smith College's Picker Engineering Program website: <http://www.smith.edu/engin-eep/homoepage.htm> & <http://www.science.smith.edu/departments/Engin/designclinic/>
[f] Woods (1996); McMaster's Department of Chemical Engineering website: <http://www.chemeng.mcmaster.ca/innov1.htm> & McMaster Problem Solving Program websites: <http://www.chemeng.mcmaster.ca/MPS/default1.htm>
[g] Nair et al. (2002) and Carnegie Mellon's Environmental Decision Making website: <http://telstar.ote.cmu.edu/environ/m2/s3/index.shtml>
[h] Michigan Technological University's Enterprise Program website: <http://www.enterprise.mtu.edu/> & Purdue University's School of Engineering website: <https://engineering.purdue.edu/Engr/Sinature>

"bolted-on" denotes that sustainability and/or PBL are acknowledged in the goals of the program; however, there is limited integration in courses or the curriculum. For example, sustainability could be "bolted-on" to a curriculum by adding an elective related to sustainable development. "Built-in" indicates that sustainability and/or PBL are stressed as an important goal of the program and significant effort has been made to integrate these concepts and methods into the

Table 2. Level of problem-based learning and sustainable thinking integration into the engineering programs at selected universities

University	Sustainability[1]	Problem-based learning[1]	Notes
Clarkson University; Environmental Engineering[a]	Bolted-on	Bolted-on	Clarkson is increasing the incorporation of environmental themes and issues into their curriculum and has received funding for an REU in Environmental Sciences and Engineering to foster undergraduate understanding of sustainability issues. PBL is encouraged, but seems to be limited to senior capstone projects (required), research (optional) and competitive design projects (optional).
Colorado School of Mines; Engineering[b]	Bolted-on	Bolted-on	CSM has a core course titled ''Nature and Human Values'' (NHV) that is required for all CSM freshman. It includes a week long introduction to humanitarian engineering that includes discussion of the roles of engineers in society and the developing world. CSM has plans to include 4 new courses in sustainability that address ethics, community technology and culture. PBL is mainly incorporated through an EPICS program which allows students to work on open-ended problems in a team environment.
Lawrence Technological University; Mechanical Engineering[c]	Bolted-on	Bolted-on	Lawrence Tech. offers a curriculum in Alternative Energy that examines alternative and renewable energy. The program is open to all engineering students can be coupled with a formal B.S. or M.S. in one of the traditional engineering disciplines. PBL learning is incorporated into the engineering curriculum through senior design projects, however student-centered learning is not commonly integrated into regular coursework.
Michigan Technological University; Engineering[d]	Bolted-on	Bolted on	Limited efforts have been made to integrate PBL and sustainability concepts at the undergraduate level, other than the Enterprise and Senior design programs. However, MTU has several graduate level programs that fully integrate sustainability and problem-based learning. They offer a certificate in sustainability, a master's option that includes two years of work with the Peace Corps (creating/disseminating technology in developing countries), and were recently awarded an Integrative Graduate Education and Research Traineeship for Sustainable Futures.
University of Minnesota; Engineering[e]	Bolted-on	Bolted-on	University formed the Institute for Social, Economic and Ecological Sustainability (ISEES) in 1996 to strengthen their commitment to sustainability issues, however focus is mostly on the social and natural sciences, with limited mention of engineering. Individuals within the school of engineering (i.e. K.R. Smith) are doing research related to use of PBL in engineering education, however PBL is not commonly integrated into the undergraduate engineering curriculum. Like other universities, all engineering students are requirede to participate in a capstone design course in their senior year that introduces them to team work and ''real-world'' problems.
University of Pittsburg; Engineering[f]	Bolted-on	Bolted-on	Through the Mascaro Initiative, undergraduates work with graduate students and faculty in inter-disciplinary teams in research projects to cultivate new green construction and water-use technologies. However, student-centered learning and sustainability are not commonly incorporated into coursework.
Purdue; Engineering[g]	Bolted-on	Bolted-on	At the undergraduate level, active learning has been incorporated through senior level capstone projects and Engineering Projects in Community Service (EPICS) program, which allows students to participate for up to four-years in applying technical skills to a loosely structured project. Sophomore and junior level students can also participate in ''cornerstone'' projects which are smaller versions of the EPICS program. At the graduate level, eight interdisiplinary engineering areas have been developed, several address issues pertaining to sustainability.
Carnegie Mellon; School of Technology[h]	Bolted-on	Built-in	Carnegie Mellon received a NSF Course and Curriculum Development Grant to increase environmental literacy at the undergraduate level. The goal of the program is for students to understand the main principles of the environmental sciences, as well appreciate the systemic nature of environmental issues. PBL is built in to their environmental literacy program and is integrated into their existing engineering curriculum.
Rowan University; Engineering[i]	Bolted-on	Built-in	Four-year sequence of courses, called Engineering Clinics, seeks to provide students with a meaningful, leading-edge, team-based, multidisciplinary project experience. however, PBL is not incorporated throughout the curriculum. Sustainability concepts are introduced in some courses and through the Research Experience for Undergraduates (REU) in Pollution Prevention and Sustainability.
Stanford; Civil and Environmental Engineering[j]	Built-in	Bolted-on	The department introduced a new Architectural Design program in 2004/2005 that offers courses in architecture and building design, with emphasis on sustainability, green design, life-cycle planning, and design/construction integration. Stanford has also restructured their department to improve sustainability of the built-environment by creating a new graduate program in ''Atmosphere & Energy'' and revamping their ''Construction Engineering & Management'' and ''Environ. & Water Resources'' graduate programs to include sustainability thrusts. In 1993, they launched a PBL Laboratory to teach students how to work in teams with individuals from varying areas of expertise.

Table 2 (*cont.*)

University	Sustainability[1]	Problem-based learning[1]	Notes
Smith College; Picker Engineering[k]	Built-on	Redesign	Humanities are incorporated into a learner-centered engineering program which emphasizes social relevance, sustainability and improvement of the human condition. PBL is integrated throughout the curriculum and a year-long capstone course is required for seniors, in which they collaborate in teams of real-world projects sponsored by industry and government.

[1] **Bolted-on**: Acknowledged in goals or mission statement of the program, however there is limited integration in courses or the curriculum, such as in one course or as a portion of a several courses at the junior or senior level (i.e. senior design).
Built-in: Stresses in the goals and mission statement of the program and significant effort has been made to integrate concepts and methods into the existing curriculum at all levels (i.e. at freshman through senior level).
Redesigned: An essential element of the program goals and significant effort has been made to rethink and redesign and program to completely integrate concept into the curriculum at all levels (i.e. at freshman through senior level).

[a] Clarkson University webpage: <http://www.clarkson.edu/prospective/academic_majors/majors/engineering_studies.html> & <http://www.clarkson.edu/cee/curriculum.html>
[b] School of Mines website: <http://www.mines.edu/academic/epics/about/overvi.html> & <http://humanitarian.mines.edu/courses.htm>
[c] Lawrence Technological University website: <http://www.ltu.edu/engineering/mechanical/alt_energy_curriculum.asp>
[d] Michigan Technological University website: <http://www.me.mtu.edu/academics/undergrads/degree_req.html> & <http://www.enterprise.mtu.edu/> & <http://www.sfi.mtu.edu/>
[e] University of Minnesota website: <http://www.ce.umn.edu/~smith/links.html> & <http://www.uservices.umn.edu/sustainableU/energy.html>
[f] University of Pittsburg website: http://www.engr.pitt.edu/ & <http://www.engr.pitt.edu/freshman/policies/index.html>
[g] Purdue University website: <https://engineering.purdue.edu/ABE/Undergrad/abe.whtml> & <https://engineering.purdue.edu/Engr/Signature>
[h] Nair et al. (2002); Carnegie Mellon School of Technology website: <http://www.cit.cmu.edu/ugweb/c_ugweb_objective.html>
[i] Rowan University website: <http://www.rowan.edu/catalogs/ungrad/programs/> & <http://www.rowan.edu/colleges/engineering/clinics/reu040>
[j] Standord University website: <http:cee.standord.edu/committee/CEE-Sus-Vision7-13-Final.pdf> & <http://pbl.stanford.edu/>
[k] Smith University website: <http://www.science.smith.edu/departments/Engin/education_centered.php> & <http://www.science.smith.edu/departments/Engin/about_philosophy.php>

existing curriculum at all levels (i.e., freshman through senior year). "Redesign" signifies that sustainability and/or PBL is an essential element of the program goals and significant effort has been made to rethink and redesign the program to completely integrate the concept into the curriculum at all levels. It was found that a majority of universities are doing so by simply inserting sustainability or problem-based learning courses into their existing curricula. However, this assessment was largely the subjective opinion of the authors and not all undergraduate engineering programs within the United States were examined. A more complete and objective methodology is needed, such as university surveys, student assessment upon graduation, indicator development and application, content analysis of curricula and/or student work-product, etc. Perhaps, it would be most effective to assimilate such a measurement into the accreditation process.

The findings presented in Table 2 and the ensuing discussion is the result of a web-based analysis of university response levels to sustainability and problem-based learning, primarily in undergraduate engineering curricula. Universities and colleges were selected through a review of sustainability in higher education literature and internet-search methods (e.g. Google), as well as those known to have received funding to support education reform for sustainability from national agencies, such as NSF. Of these academic institutions, those without adequate information available on their website (e.g. course syllabi, degree requirements, departmental vision and mission statements) to properly identify the level of incorporation of sustainability and PBL into their programs were removed. In addition, engineering programs without documented efforts to include PBL and sustainability were not examined. A web-based approach was selected because: it is possible to complete with a limited budget; websites transmit the institution's values, image, and self-perception to the world; and websites are becoming an important information source [30]. However, such an approach has limitations. Websites may not contain information that is current, accurate, or complete—they may not accurately reflect the institution's response level. In addition, the results may be biased toward institutions that can afford to establish a more elaborate site.

We identified only one university, from those assessed, that has made a significant effort to "redesign" its engineering curriculum in terms of both sustainability and pedagogy. A majority of the examined universities bolted-on or built-in various components of either sustainability or PBL into their existing program(s), but few have made significant changes or efforts in both areas. Redesign of *graduate* level programs was noted at universities such as Michigan Technological University, Purdue, and Stanford (Table 2). However, the benefits of these reforms have not yet reached the undergraduate level.

Of the universities examined, the Smith College Picker Engineering Program stood out as a leader in engineering curriculum transformation (Table

2). In its philosophy statement, the program has dedicated itself to "redefining engineering education" in order to produce engineers that "appreciate and understand the human condition" [31]. They are accomplishing their goals by using PBL, concept maps, and reflective narratives throughout their curriculum. These methods facilitate deep-level understanding and help students visualize the "big picture." The program also empowers its students and encourages them to take charge of their own learning, by allowing them to direct learning experiences (e.g. homework, assessment) that best meet their needs. In addition, Smith College is putting engineering in a social context to produce a more diverse group of globally oriented engineers [32–33]. Smith College uses its strength in the liberal arts to incorporate social relevance, sustainability, open-mindedness, and creativity into its engineering program. This provides their graduates with an awareness that graduates from other institutions generally lack.

The ability of Smith College's Picker Engineering Program to more fully integrate sustainability and social issues into their engineering curriculum most likely stems from two important factors: (1) it was able to start from a "clean slate" when it was established in 1999, and (2) the timing of the programs conception coincided with a proliferation of knowledge on PBL, as well as an increasing global awareness of sustainability issues. They did not have to overcome the barrier of reforming or reorienting a current system. They had the freedom to "redress the problems entrenched within traditional engineering curricula" [32]. Starting from a clean state also allowed them to select faculty who shared their vision of engineering education. It is interesting to note that Smith is a women's college. Possibly, Smith's success in integrating humanitarian and social concern into its engineering program can be explained using Belenky's model [10] of intellectual development, which suggests two separate patterns of procedural knowledge, separate and connected. Women tend to posses more *connected* learning patterns, which include empathy, understanding, and caring [10, 8]. In other words, consideration of the "human condition" may come more naturally to women than to men. However, a more detailed study is needed to establish a connection between gender and sustainable thinking.

INCENTIVES AND BARRIERS TO CHANGE

For most universities, the question remains: why is there reluctance to reform or redesign engineering education to embrace sustainability through student-centered learning? The answer may lie in the deep-rooted structure of current institutional systems and the lack of incentive for change. In the following section, we attempt to address some of the factors influencing a university's level of response to the call for educational reform and the development of sustainable thinking.

University influences

The fundamental issue that must be addressed to achieve education reform and the effective incorporation of sustainability principles is overcoming people's basic resistance to change. Entire universities, academic departments, individual faculty members, and students are all plagued by a resistance to change. To reorient engineering curricula toward deep-level learning, particularly of sustainability concepts, requires a close examination of the incentives and barriers to change.

Within the university, effective organizational structures are necessary to permit and promote the development of effective instructional methods [34]. Fink generates a useful model of multidimensional institutional effectiveness which is helpful in identifying areas for improvement (see Fig. 2). The model also indicates that these areas are interrelated. For example, educational programs must be established that are capable of meeting educational goals and are adequately supported by organizational structure and university policies and procedures.

To incorporate learner-centered educational programs and sustainability into undergraduate engineering curricula, universities must have a set of educational goals that reflect these priorities. Then, they must establish programs capable of achieving these goals. This means that there must be multiple opportunities within the curricular structure to engage in problem-based learning and apply sustainability concepts. The organizational structure of the university must also support its goals. Most universities are structured around discipline-based departments. In order to promote the interdisciplinary learning necessary to address sustainability issues, other structures must be developed.

Fig. 2. Organizational structures to support intellectual development and understanding of sustainability in undergraduate engineers (adapted from Fink 2003).

Recently, Purdue University [35] restructured its engineering graduate program by establishing eight multidisciplinary "signature areas". These areas are based in engineering but include faculty in related fields. One area of particular interest is Global Sustainable Industrial systems, which examines the ecological, social, political, and economic impacts of industrialization. Graduate students have the opportunity to work on multidimensional problems with experts in a number of fields. Restructuring of this nature would be beneficial to undergraduate level engineering curricula, as well.

Many university policies and procedures impact the ability to attain the goals of deep learning and integration of sustainability. However, one of the greatest barriers to educational reform is the policies related to faculty work [34]. Splitt identifies this barrier as the academic version of "the innovator's dilemma" [36]. In industry, the innovator's dilemma is that both success and failure are determined by: (1) response to customers and (2) aggressive investment in technology, products, and manufacturing capabilities that satisfy customers' needs [37]. Although adopting innovative ideas may result in success, shifting the focus from perfecting the current product or process to a new strategy, such as biomimicry, may be insurmountably disruptive and lead to failure unless the benefits to such a shift are great. The current dilemma within academia is that integrating concepts of sustainable development and business into engineering curricula does not complement the current rewards and recognition systems in place at most of our educational programs [36]. Faculties acknowledge that creating significant learning experiences and integrating sustainability concepts are "good ideas." Unfortunately, they do not believe that their institutions typically provide incentives for improving their teaching—they only recognize and reward faculty for publication and for teaching courses [34]. In economic terms, the marginal costs of engaging in educational reform outweigh the marginal benefits.

In addition, assessment methods must be adopted that effectively measure the progress toward educational goals. Problem-based learning presents a unique challenge for assessment because the focus is on students learning-to-learn and less on the mastery of factual knowledge [16]. Therefore, traditional assessment methods are not effective in measuring the skills and intellectual development that PBL promotes. Alternative forms of assessment are needed to measure: (1) creativity, (2) the willingness and ability to continue learning, and (3) a personal initiative and self-direction [38]. Portfolios, presentations, journals, critical reflections, activity logs, and essays may be more effective tools.

Outside influences

Accrediting agencies, funding agencies, and disciplinary associations are in a position to provide considerable support in the overall effort to promote better teaching [34]. Splitt [2] and Ashford [39] argue that change is unlikely to occur in most engineering programs without a strong forcing function. The "force" applied by those with an interest in engineering education reform toward sustainability has been mixed. Institutions outside of the university, such as accreditation agencies, funding sources, industry, and professional organizations, provide universities with notable incentives and barriers to change. Of these, the influence of accreditation agencies and industry are the most significant.

ACCREDITATION AGENCIES

The Accreditation Board for Engineering and Technology (ABET) is charged with the task of "quality assurance in higher education" for programs in applied science, computing, engineering, and technology. Of particular interest are ABET's requirements for program outcomes and assessment, which identifies the knowledge, skills, and behaviors students should have when they graduate from an engineering program [40]. These requirements include necessities such as training in math, science, engineering principles, and problem-solving. However, ABET also stresses that engineering students should possess the ability to: (1) function on multidisciplinary teams, (2) communicate effectively, and (3) understand professional and ethical responsibility. In addition to the above requirements, "sustainability" is included as a "realistic constraint" for consideration in design. Furthermore, sustainability concepts are alluded to in the ABET requirement that students attain "the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context" [40]. These requirements are general guidelines that must be fulfilled by the university for basic-level accreditation of the engineering program.

The ABET requirements discussed above are the 2005–2006 criteria. It is important to note that these criteria are the most recent product of a lengthy evolutionary process toward incorporating sustainability and deep learning. "Sustainability" and "environment" were added this year to the list of reasonable design constraints and the list of systems impacted by engineering solutions, respectively. Interestingly, ABET's list of realistic constraints also includes: social, ethical, and heath and safety. Although ABET has increased its efforts to reorient engineering curricula toward sustainability concepts, more direct emphasis on the skills and knowledge necessary to support sustainable development is needed. Furthermore, it may be more appropriate to list issues such as sustainability and ethics as values or principles engineers are responsible to abide by as opposed to design constraints.

INDUSTRY

Industry provides some support for sustainability and education reform, but industry's efforts must be enhanced. Their involvement in undergraduate engineering education represents both sides of the market. On one side, industry supports the production of engineers by supplying funding to universities. On the other side, it consumes engineering graduates. They have a vested interest in the quality of education students receive and have lobbying power as an interest group.

In this case, industry faces an innovator's dilemma in the conventional sense. Investing in a change in university pedagogy and curriculum that includes problem-based learning and sustainability concepts may provide society with engineers capable of addressing complex problems in a sustainable way. However, this type of engineering education reform may ultimately cause traditional industries to fail. Sustainable solutions to society's needs may mean the elimination of the role of traditional industries within the market. A further disincentive to promoting engineering educational reform is the length of time between investment and payoff. Investing in changes to engineering curricula may take 15 years to generate measurable benefits [41].

Industries do provide support for problem-based learning through funding of capstone projects and involvement in enterprise programs such as that at Michigan Technological University. While these programs are an excellent opportunity for undergraduate engineering students to gain "real-world experience," they are lacking in several areas. First, the capstone projects are generally limited to one year (usually the senior year) and emphasize traditional engineering. Enterprise programs are a step toward integration of PBL in engineering curricula because students often have the option to participate for up to three years in various aspects of the project. Industry perceives improved communication skills and business knowledge gained by graduates as a benefit to participation in such programs. Additionally, they get a product or service in return.

A second concern is the actual level of commitment to sustainability within industry. For example, Ford Motor Company indicates that it is "a leader in environmental responsibility" and goes on to state that its "integrity is never compro-

mised" [42]. However, a critical examination of Ford's Health and Environmental Policy reveals a slight contradiction. The policy states: "Company products, services, processes, and facilities are planned and operated to incorporate objectives and targets that are periodically reviewed so as to minimize, to the extent practical, the creation of waste, pollution, and any adverse impact on health and the environment" [43]. This seems to suggest that, in some cases, practicality will trump sustainability issues.

CONCLUSIONS

Successful integration of sustainability into engineering curricula requires a change in the approach to education. Students need not only the knowledge base to generate effective engineering solutions; they need the intellectual development and awareness to understand the impact of their decisions. Learner-centered environments are a prerequisite to the redesign of engineering education for sustainability. We examined a number of universities to determine their response to the call for inclusion of sustainability concepts into engineering curricula. A majority of the universities we examined "bolted-on" various components of sustainability or student-centered learning into their existing programs. Only one university examined has made significant efforts to redesign engineering education in terms of sustainability *and* pedagogy. There are a number of barriers that hinder the reorientation of engineering curricula toward "sustainable" engineering; these barriers include: (1) the culture and organization of universities, (2) ABET's program and reporting requirements, and (3) the nature of support provided by funding agencies and industry. Although this paper provides a good initial investigation into the integration of sustainability and learner-centered environments into engineering curricula, a more thorough objective analysis is needed.

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