Sustainability **2012**, *4*, 72-91; doi:10.3390/su4010072

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

On a Vision to Educating Students in Sustainability and Design—The James Madison University School of Engineering Approach

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Received: 14 November 2011; in revised form: 22 December 2011 / Accepted: 23 December 2011 / Published: 29 December 2011

Abstract: In order for our future engineers to be able to work toward a sustainable future, they must be versed not only in sustainable engineering but also in engineering design. An engineering education must train our future engineers to think flexibly and to be adaptive, as it is unlikely that their future will have them working in one domain. They must, instead, be versatilists. The School of Engineering at James Madison University has been developed from the ground up to provide this engineering training with an emphasis on engineering design, systems thinking, and sustainability. Neither design nor sustainability are mutually exclusive, and consequently, an education focusing on design and sustainability must integrate these topics, teaching students to follow a sustainable design process. This is the goal of the James Madison University School of Engineering. In this paper, we present our approach to curricular integration of design and sustainability as well as the pedagogical approaches used throughout the curriculum. We do not mean to present the School's model as an all or nothing approach consisting of dependent elements, but instead as a collection of independent approaches, of which one or more may be appropriate at another university.

Keywords: sustainable design process; engineering education; curriculum development; pedagogy; sustainable values; individual behavior

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1. Introduction

Declining environmental conditions world-wide require a response from the engineering community. Quite literally, engineering as a discipline has to evolve to meet our growing understanding of global and local conditions related to the environment and as well as its influence on a variety of issues related to human well-being. Engineering is a creative and integrated discipline; however, it is only in the last two decades that there has been widespread realization of the profound and growing influence engineering, and engineering design especially, has on all sectors of society. We have come to understand that the greatest and most immediate sustainability problems humans face relate to our relationship with the natural world. This places a great deal of responsibility on a discipline that, heretofore, has taken little responsibility outside its own sphere of technical influence.

As engineering becomes an increasingly integrated discipline, engineers and engineering faculty need to determine the appropriate integration of social sciences, sustainability, and artistic disciplines. In short, we need to redefine the discipline to meet the needs of an increasingly technological society that accepts few boundaries related to a global standard of living. While it might go too far to say that engineering needs to become a humanistic discipline, it clearly does need to be a *more* humanistic discipline, quite simply because so many of our human activities are related to and dependent upon products and processes engineers design and develop. As we have no doubt learned, and as is reflected increasingly in academia and industry, the answers to many human problems are not to be found in specific and discrete disciplines. We need to determine which disciplines need to be integrated into engineering practice as we continue to address critical problems facing our planet and people. This is a profound obligation and an exciting challenge, especially for higher education.

Engineering programs need to address this dilemma training students to think flexibly and to be adaptive. Students need to become versitalists. Versitalists, as popularized by Friedman, can "apply depth of skill to a progressively widening scope of situations and experiences, gaining new competencies, building relationships, and assuming new roles" (p. 291, [1]). Academic disciplines (the sciences and engineering especially) are no longer discrete, and consequently, *new engineering programs* need to focus on the future of the discipline rather than on the rather stable conditions that characterize current engineering work. The School of Engineering (SOE), James Madison University's (JMU) first engineering program, has been developed as a new program from the ground up to provide students with the knowledge and skills necessary to address these challenges. In this paper, we present the SOE approach for integrating sustainability and engineering design into and throughout an undergraduate engineering degree program curriculum. We review our definition of sustainability, the pedagogical approaches employed throughout our curriculum, and evidence supporting our model from a National Science Foundation sponsored study.

2. Literature Review

Design and sustainability are not mutually exclusive; however, they are often taught that way. Both design and sustainability transcend traditional disciplinary boundaries. If we are to prepare our students to deal with the complex problems of sustainability, we must provide them with a holistic education incorporating all contexts of sustainability [2-8]. Huntzinger *et al.* argue for a change to the traditional educational approach to one where sustainability and problem-based activities are not just "bolt-on" additions, but are instead integrated into the curriculum [9]. Azapagic *et al.* seem to agree, arguing that "sustainability must become part of their [engineering students] everyday thinking" (p. 14, [10]), and additionally, education in sustainability must be "an integral part of engineering education programs, not a mere 'add-on' to the 'core' parts of the curriculum" (p. 14, [10]). Shriberg states that "Sustainability education needs to be incorporated into core curricula and courses in many disciplines" (p. 261, [11]), illustrating that the problems of sustainability are not limited to engineering. Wals and Jickling argue that "a curricular review in terms of sustainability integration is per definition of an interdisciplinary, systemic and holistic nature" (p. 227, [8]). Additionally, Wals and Jickling stress that sustainability education "concerns cognition, attitudes, emotions and skills" (p. 227, [8]) and "includes deep debate about normative, ethical and spiritual convictions" (p. 227, [8]).

An education in sustainability must be interdisciplinary, providing the knowledge and skills for students to understand and consider the impacts of their decisions in many sustainability contexts (often three contexts are considered: People, Prosperity, and Planet [12]). Huntzinger *et al.* stress that "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" (p. 219, [9]). Unfortunately, in engineering this has not been the customary approach to sustainability education. Traditionally, two engineering sub-disciplines have been the primary focus: green engineering and environmental engineering. In general, green engineering has focused on design that is in greater long-term harmony with the environment, while environmental engineering has addressed the deleterious effects engineering has had on the environment [3,13]. Consequently, as discovered in a survey of students at the University of Plymouth, students often do not learn to perceive sustainability from a systems perspective; instead students "associate the concepts uni-dimensionally with the environment rather than embracing a holistic (multi-dimensional) interpretation" (p. 329, [5]). Further, Segalàs *et al.* find that "most students, after taking a course on SD, focus on the technological aspects of sustainability, regarding technology as offering solutions to environmental problems" (p. 283, [14]). They conclude that courses focusing on sustainable development need to place a stronger emphasis on the social context of sustainable. However, as Azapagic *et al.* point out, this is markedly difficult in engineering where the students often perceive sustainability "as 'soft' science, whilst their interest lies in 'hard' engineering" (p. 11, [10]).

While universities have begun to integrate instruction in sustainability into their curricula to varying degrees [9], much of this instruction has been narrowly focused on environmental issues. The issues of sustainability are, however, broader than this single context of sustainability. The issues of sustainability must be considered from a systems theory perspective where sustainability factors comprise a complex system, and a change in one context is likely to result in an unpredictable change in the others [15-17]. Consequently, we must be educating our students to investigate how their decisions as engineers influence systems which they design [18]. This is in line with the Barcelona Declaration, which summarizes an engineer as, "… one who has a long-term, systemic approach to decision-making, one who is guided by ethics, justice, equality and solidarity, and has a holistic understanding that goes beyond his or her own field of specialization" (p. 1, [19]).

At Cambridge University, the Department of Engineering has worked to incorporate education into sustainable development across the department by focusing on interdisciplinary and systems thinking, but the department has struggled to maintain balance as "introducing sustainable development elements generates tension between the traditional quantitative and the more current qualitative understandings of the issues" (p. 235, [20]). Other universities have taken a more scaled-back approach, implementing "bolt-on" additions to the curriculum [9] by developing educational resources such as new courses and course projects [21-23], multidisciplinary case studies [24], educational modules [25-28], and role play simulations [29].

While full integration of sustainability principles into curricula has been difficult, it has, however, been interdisciplinary. For example, at the University of Bristol, educators have developed an interdisciplinary, team-taught sustainable development course open to all majors "to demonstrate the potential application of sustainable development ideas across a wide range of contexts" (p. 475, [30]), and similarly, an interdisciplinary project course at the University of Cincinnati pools business students, industrial design students, and environmental studies students to apply sustainable development principles to projects for real-world clients [22]. At the University of Manchester, modules "focused on the professional skills required to drive change towards sustainable development" have been piloted to educate the engineering and science students to "the wider implications of global societal responsibility" (p. 72, [26]).

Implementing change in the curriculum to educate students in sustainability is essential, but changes must be accompanied by valid assessment to ensure that the desired objectives are being achieved. To assess individual course outcomes and assist with new course development, Riley *et al.* developed a course outcome-based rubric—termed Sustainability in Higher Education Assessment Rubric (SHEAR) [21]. Their rubric provides key course components identified in successful sustainability-focused courses and course outcomes [21]. Concept (or cognitive) maps have been used to assess how well students have learned sustainability concepts and their interconnectedness [31-33]. Concept maps have the benefit of providing a consistent assessment metric for longitudinal learning of sustainability concepts. In Germany, key competencies (under the BLK 21 Program) have been developed in response to the United Nations' Agenda 21 [34] that provide measurable curricular outputs to assess students' knowledge of, and individual values and behaviors, toward sustainable development [35]. At the University of Plymouth, a student survey administered across campus is used to assess "students' current understandings and perceptions of, and attitudes towards, sustainable development, and related concepts and issues" (p. 332, [5]). Survey findings, however, reveal a "dissonance" between student perceptions and educational outcomes [5]. Shriberg proposes that assessment activities should go further than curriculum assessment or the validation of key competencies, arguing for campus-to-campus assessment of campus-level sustainability efforts [11].

Beyond knowledge retention, outcomes-based assessment should also focus on the values, attitudes, and behaviors of the students [36]. Education in sustainability must engender the values and behaviors of students that allow them to make educated, sustainability-informed decisions. To do this, values must be a key part of any course in sustainability [37]. Mulder describes that a "University education is about sharpening critical minds that are able to make balanced appraisals of their subjects of choice and the norms and values to use in this appraisal" (p. 76, [38]). Similarly, Barth *et al.* stress the importance of instilling ownership of learning so that students can not only generate and acquire new knowledge but also reflect on their own behavior and values [39]. Mulder warns, however, that the norms and values of sustainable development should not be dictated as this can cause students to neglect future messages [38]. One approach to engender sustainability based individual values and behaviors is a hands-on, learning module being developed at RMIT University in Melbourne that allows students "to foster values and behaviors, deepening their understanding of the issues, and allows them to recognize the importance and complexity of the decisions they will be asked to make in their professional lives" (p. 158, [25]). Arbuthnott, however, warns that changed values and behaviors do not always result in an intentional change [40]. Arbuthnott also stresses the importance of providing an environment that fosters individual change, and that programs should "plan education aimed at helping people translate their intentions into action" (p. 153, [40]). This is what the JMU SOE aims to achieve.

3. Sustainability in the School of Engineering

Conceived by a task force of interdisciplinary faculty (from business, education, policy, science, math, technology, and engineering disciplines) beginning in December 2005, the School of Engineering at James Madison University is meant to be a different type of engineering program—one integrating instruction in liberal arts, business, engineering, math, and science [41]. The program was designed as a single undergraduate engineering degree that spans traditional engineering disciplines (e.g., electrical, mechanical, civil) and focuses the program on *engineering design, integrated systems analysis,* and *sustainability in four contexts (environmental, social/cultural, economic, technical).* Our programmatic goal is to enable our students to understand sustainability from a systems perspective where changes or decisions made in one part of a system can (and likely will) cause a perturbation in another part. Through an innovative curriculum and a variety of pedagogical approaches, we educate students to have the cognitive flexibility to solve the engineering challenges posed by design for sustainability.

The SOE strives to provide a holistic curriculum through the integration of the JMU liberal arts core and several sequences of engineering courses on engineering design, business, technology management, engineering science, sustainability, and systems analysis [42]. Students take a six-course design sequence, culminating in a two-year (four-semester) capstone experience. Students take two sustainability courses—one focusing on fundamental engineering and science principles, and the other focusing on socio-economic considerations, industrial ecology, and product and process life cycle assessment. Further, students learn to understand and apply sustainability in four contexts (environmental, technical, economic, and social) by means of instruction, case studies, and projects with the goal that students ultimately will apply these principles in their professional careers, their private lives, and as global citizens.

At JMU, we recognize that sustainability must be taught in a variety of contexts and must stem from our graduates' intrinsic values. Therefore, we extend the more traditional sustainability definitions (such as the 1987 Brundtland Report [43]) to:

> *A society possessing the ability to continue to survive and prosper, not just with respect to environmental resources and economic development, but also with respect to quality of life as it pertains to conditions that promote sustainable human prosperity and growth (e.g., opportunity, economy, privacy, community, the arts, education, and health); a sustainable*

> *society meets these needs simultaneously, and in the context of human respect and the ability to negotiate differences without violence* (p. 7, [44]).

Sustainability, therefore, focuses on more than the simplistic viewpoint that stresses the treatment of environmental resources and the inevitable waste resulting from the production of goods and services. We define sustainability in the following four contexts—environmental, social, economic, and technical—as follows [42,44]:

Environmental Sustainability deals with the engineering of processes, products, and structures which has, indefinitely, a less negative, a neutral, or a benign effect on all environmental systems. *Students should learn to design products and processes to minimize use of our energy and material resources. Students learn to consider these limitations over the entire life cycle of the design, including manufacturing, assembly, distribution, use, and end-of-life recycle/reuse/recovery/disposal.*

Social Sustainability includes the role of individuals, relationships among social groups, the family, collective behavior, social class, race and ethnicity, medicine, education, and the role of institutions in society. *Students learn the influences that a design has on individuals, communities, regions, and cultures are central to the development of sustainable products and processes. This includes the analysis of policies, practices, and other social factors on long-term community development.*

Economic Sustainability pertains to profit-making policies and strategies related to the design and development of a process, product, or service; economic sustainability addresses factors that influence the economic health and profile of communities, including the standard of living, the business climate, employment, and the productive role of the corporation in the life of a community. *Students learn to analyze and meet short-term (cash flow) and long-term (balance sheet) economic requirements of product and process designs. This includes more than simple return-on-investment, but also includes imbedded environmental and social costs of a product or process.*

Technical Sustainability addresses a wide variety of factors related to the design and manufacture of products, especially the (1) scientific research and appropriate technology (compared to alternatives) supporting product design, function, and development; (2) ease and efficiency of durable construction and use; (3) maintenance and functioning capabilities that meet the objective for which a product is designed; (4) material selection; and (5) reduction, recovery, reuse, or disposal of parts and unused materials. *Students learn that a design must meet the technical requirements of the product or process under consideration. In short, the design must work in the desired application for an appropriate amount of time.*

Three factors inform our approach to integrating sustainability instruction into the curriculum. First, we recognize the inherent value of approaching sustainability employing a *systems theory* methodology. Second, we consider *values* (whether it be corporate, government, community, or individual) as the principle guiding force for defining and solving sustainability problems. Third, following years of researching and teaching sustainability, we understand it is an individual's *behavior*, not simply his or her *knowledge* of sustainability, which supports and promotes sustainability. Our approach to teaching sustainability is, therefore, focused on students' values and behaviors as an effective method for motivating sustainable behaviors. Our primary objective is to help students develop values and behaviors in a wide variety of academic disciplines they can use to solve sustainability problems in their lives, careers, and communities.

Systems Theory: Determining the sustainability of a system (whether the system is a product, process, or human activity) depends upon the careful and complete *assessment and evaluation* of a range of technical and human factors, and their influences on each other, noted in *The Engineer of 2020* as “the core analysis activities of engineering design” (p. 54, [45]). This approach is central to sustainability efforts, but it is a methodology about which too little has been written or practiced. Because sustainability factors comprise a *complex system*, a change in one factor is likely to result in an unpredictable change in the others [15,16].

Values: The underlying principle for learning sustainability or exhibiting sustainable behavior is values [46], defined as beliefs in, or demonstrations of, the significance and meaning of objects, qualities, or human behaviors. When solving sustainability problems, we are confronted by a decision we must make according to our values related to human well-being and survival [47]. As individuals and as a society, we must understand the value-related ramifications of our actions on a host of factors that determine sustainable practices [48], whether they be corporate, community, or individual. Students generally embrace admirable values related to sustainability, but often encounter a “cognitive dissonance” when asked to explain whether their actions accurately reflect their values [49]. In short, students often do not act according to their values and beliefs.

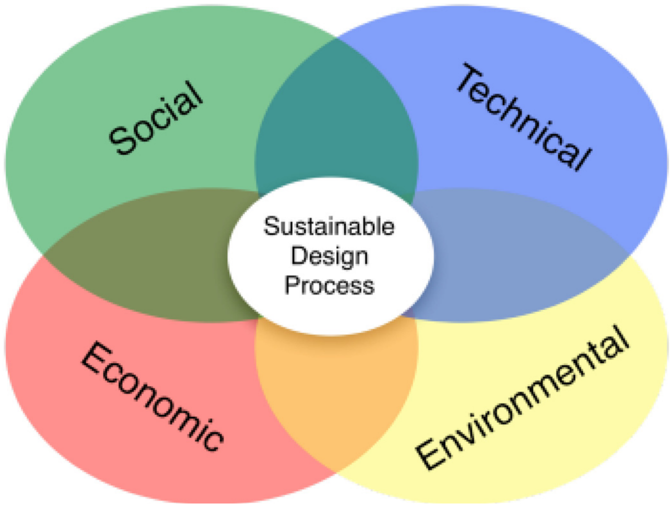
Individual Behavior: While instruction in sustainability that increases students knowledge appears to have an influence on students’ behaviors [50], there is research to support that instruction that tends to change students’ behaviors is longer lasting [18]. The problem in much of our current instructional methodologies: Encouraging environmental (or other) ideas and actions offers “opportunities” to be more sustainable, but increasing knowledge does not necessarily change values or help change behavior. We acknowledge the idea that productive change often starts with the individual and is reflected then in collective (community) behavior. If one understands the complexities and interconnectedness of sustainability as related to one’s own life, then he or she might well transfer this systems knowledge to understanding community and global sustainability. The theoretical foundations for this learning process are generally constructivist in nature. Csikszentmihalyi [51] notes that an individual making a creative contribution in a societal context “…must also reproduce the system within his or her own mind” (p. 47, [51]). As well, Bruner, suggests that the self-regulatory nature of learning moves in the direction of more sophisticated concepts and broader applications [52]. Theories advanced by Piaget in most of his works on children and adolescents support this theory [53].

4. Design and Sustainability

We believe that the requirements of each of the four sustainability contexts (social, technical, economic, and environmental) must be balanced in a sustainable design process, and “unless and until these four elements are equally incorporated into the learning objectives of engineering design curricula, engineers will not truly be answering the call to participate in the design of sustainable societies” (p. 4, [41]).

As Figure 1 illustrates, the social, technical, economic, and environmental contexts must come together synergistically. Consequently, as we teach students design, we strive to integrate sustainable thinking into their thought and decision making processes. It must be an integral factor in all of their design work. A variety of instructional topics covered in the design sequence that help us to achieve this goal follow.

Figure 1. The Balanced Integration of Environmental, Social, Economic, and Technical Sustainability creates a "Sustainable Design Process."



Critical Thinking, Decision Making, Assessment, and Evaluation: Critical to effective and innovative design are the thinking practices that go into the analysis and evaluation of a problem as well as conception of a product or process that will address a problem. Instruction in design focuses on cognitive processes that constitute the "conceptual" component of a design. In the past, design in engineering has primarily focused, oddly enough, on the "construction" phase of the design process. Critical assessment and evaluation, while traditionally a component of the design process, have been limited to established and very linear forms of thinking. How a designer thinks, the actual cognitive processes a designer employs to generate an idea or solve a problem, has occupied no or very limited instructional time in established engineering curricula. Perhaps this is because engineering design instruction has not moved across disciplines until the last decade.

Thinking skills in engineering design grow out of two disciplines: art and psychology. The creative thinking *processes* artists use to create a "product" are no different than those employed by creative engineering designers. At the same time, the very individual cognitive skills learned and practiced by artists emerge largely from the metacognitive strategies studied and practiced by psychologists.

There is less mystery and confusion here than many believe. While the products of artists and psychologists are likely quite different from those of engineering designers, the methods used in these disciplines that focus on *thinking processes* yield innovative ideas and designs, as well as solutions to problems in virtually any discipline.

Instruction in developing *the intentional and directed intellectual processes and habits that foster effective thinking* is a foundational skill upon which all innovative design skills are ultimately dependent, especially when human factors, and the inevitable problems they create, are integrated into the technical design equation.

Aesthetics of Design: Aesthetics is that which can be perceived through the senses. Individuals respond very personally to what they consider aesthetically appealing and what is not. All one's senses, cultural and historical norms, and personal notions of harmony and "appropriateness" are employed in determining the aesthetic quality of a design. As an integral component of design, effective aesthetics invites and supports use, as well as augments the psychological benefits of a design. Aesthetic design is a form of communication and is the link between technical and commercial feasibility (product appeal and marketability). Designs that do not take these factors into account risk rejection by the user.

Instruction in aesthetics is more than adjunct to design conception, especially if a device or product is to be marketed to, or used by, the public and need not be sacrificed for function. Logic is not the central or only factor in the design of a product; a product must speak to culturally accepted norms of beauty, value, balance, proportion, and natural body movement.

Engineering students at JMU study aesthetics from a conceptual and functional point of view in order to understand how successful aesthetic design invites sensible and practical use that is not divorced from properties related to cost, usability, durability, and manufacturability…lest it hinder or sabotage the design. For this reason, our design curriculum includes instruction in human factors in design, and those related to economic viability and product testing.

According to Alaistar McDonald, head of Product Design Engineering at the Glasgow School of Art, before developing aesthetic content for any product, it is important to understand the following:

- the factors affecting product use and choice;
- the prospective users' needs, preferences, and expectations; and
- the environments in which the product is bought and used (p. 8, [54]).

It is important for students to understand the role aesthetics plays in the design process including (1) the scope and analysis of factors going into a design, (2) the success of a design (usability), (3) the role of the user in the design and testing process, and (4) the criteria that determine user satisfaction.

In short, aesthetics influences user interface—how a user feels about a product or process—and helps determine if, how, and how often a product is purchased or used, or a process employed successfully [55]. Designing for sustainability need not sacrifice aesthetics for function, practicality of construction, or economics (costs or marketing). The aesthetics of a product or design (e.g., the style with which a process is implemented in an organization) is not divorced from the sustainability: that which meets the natural aesthetic favor and functional ease of a user is more likely to persist and survive.

Design Ethics: In many cases, ethics in sustainable engineering design has been considered mostly the environmental issues related to material selection and processing, waste and the processing of waste products, public health, and the long-term analysis of the negative environmental effects of these factors.

Ethics in design more broadly defined includes topics related to the consequences design has on the human and social contexts described above, especially the conditions under which humans work and live, profit, marketing and advertising, and the equitable use of global resources (among others).

More specifically, topics that influence design and use may address the following issues related to corporate and university responsibility: environmental responsibility, personal and professional values, professional responsibility, business ethics, employee (or student) policies, and research and publication practices.

Ethics applied to these contexts is a necessary component of sustainable engineering design and must be considered in the overall design process. What will not harm the environment may still result in negative influences on a variety of complex human issues and institutions.

Technical Design Skills and Engineering Science: Although technical design skills are not specifically considered a "human factor" in design, one's approach to learning and applying technical design skills must reflect a understanding of, and sensitivity to, the contexts in which these skills will be employed, and products and processes that result.

Competence and practice in technical design include (but are not limited to) skills stemming from the engineering science courses in our curriculum. Our engineering science courses blur the traditional boundaries by combining courses that are traditionally offered independently into single classes. Developed combinations include: (1) statics and dynamics; (2) circuits, electronics, and instrumentation; (3) thermodynamics, fluids, and heat transfer; and (4) solid mechanics, material science, and material selection.

5. JMU SOE Design Sequence

The engineering design sequence begins during a student's first year in the engineering program with the *Introduction to Engineering* course. Following the introductory course, students begin the six course engineering design sequence that culminates in the four-term capstone experience. A description of the three key elements of the engineering design sequence follows.

During the *Introduction to Engineering* course, modules spanning the curriculum expose students to the expectations and culture of the School of Engineering, as well as introduce students to engineering design, engineering science, and sustainability. Students meet twice weekly for 100 minutes in our Freshman Engineering Design Studio which consists of two rooms—one with instructional space for lectures and software training, and another for construction activities with light-duty machine tools such as a drill press, band saw, and hand tools. During the course, students are introduced to software tools as well as hand and machine shop tools. Instructional modules introduce students to engineering design through reverse engineering exercises. Modules cover basic science and engineering science topics beginning with chemistry and physics and then build on how these sciences relate to engineering design. Sustainability issues discussed throughout the course include life cycle assessment, social sustainability and social justice, green economics, and energy.

Sophomore Design is a two-course sequence focusing on teaching students the process of design. The sequence follows a five phase design process including: planning, concept development, system-level design, detail design, and testing and refinement [56]. Students learn and apply engineering design tools and methods to a sequence-spanning (two-semester), real-world, problem-based, service learning project [57]. During the first term, students work in groups of five to six students through the planning and concept development design phases; then during the second term, groups are scrambled, and students work in groups of ten as they revisit the first two phases and complete the remaining three. The project for the sophomore design sequence, which is currently on its third run, is to design a pedaled cycling vehicle for a real client with cerebral palsy.

Sustainability is a common theme through the sophomore design sequence, from the beginning assignment of the term through the final deliverable. Students read McDonough and Braungart's

Cradle to Cradle [58] and consider its message as they perform concept evaluation and selection, the materials (such as reuse and disassembly) they use in their project, the life-cycle of their design (considering this is, perhaps, the only time their client will be able to have a one-off product such as this made), the emotional impacts of their final product to the client's family, and the broader impacts of their design. The goal in this course sequence is to move students toward understanding the ethical concerns that they will be forced to consider as they work on future engineering projects.

In the *Capstone Experience*, students work in groups of four to six engineering students with one or more faculty advisors on a four-semester, two-year project. In this four-semester sequence, students apply the engineering design process, and design tools and methods employed during the sophomore design sequence to their new projects. Current projects range from biology-inspired designs, to robotic systems, medical testing systems, to a sustainability-themed solar-hydrogen energy system, and a campus dining hall composting reactor. Projects were proposed by faculty members, and students bid into teams. Each student was placed in either his or her first, second, or third choice project. All engineering students entering teams have similar engineering background (*i.e.*, they have completed the SOE freshman and sophomore year engineering courses). Over the course of the next two years at JMU, the engineering students begin to specialize their degrees through their technical electives. Some students choose this specialization based on their capstone projects, while others choose this specialization based on graduate school plans and career goals. Many of the teams have also gained a multi-disciplinary experience through a pairing with non-engineering students (e.g., business students (for project planning purposes), industrial design students, computer science students, health and human services students).

Course instructional time is divided between formal class instruction and small group instruction with faculty advisors. The full class instruction time does not necessarily provide direct guidance for students in their capstone projects; instead, the majority of the class periods focus on professional skills such as technical writing, oral presentations, team and collaboration, cognitive development as well as intentional self-development through direct consideration of ethical values, beliefs, and behaviors. During these full-class instruction periods, students consider and solve unstructured problems related to design and sustainability through cases studies using visualization, writing, and personal reflection. Students explore reciprocal effects of their potential decisions and the related ethical dilemmas inherent in environmental, social, and professional contexts. With respect to design, students also learn about product testing, design aesthetics, psychology of design, market analysis, holistic design, and design ethics.

During the other weekly meetings, teams focus on the technical aspects of their projects with their faculty advisors. It is during these meetings where faculty advisors help guide their students through the engineering design process. Faculty advisors also provide domain specific information pertinent to their capstone team, and these meetings vary greatly depending on the specific project.

Our goal is for students to consider their individual values as members of a global community. We believe that values are the basis for sustainability, and since simply offering the opportunity to learn about sustainability does not necessarily lead to more sustainable behaviors [46], we instead provide critical thinking exercises and personal development activities to guide students to consider and develop their own values. It is this development of individual values that provides the motivation for students to behave in a manner more congruent with sustainability principles [59].

6. Pedagogy

Instruction in the JMU SOE combines different pedagogical approaches creating a developmental instructional environment that aims to engage our students in different modes of thinking, learning, and problem solving. A number of interdisciplinary methodologies are used throughout the curriculum; these include:

Moderate instruction over long period of time in the curriculum: Skills and attitudes students learn and practice over a long period of time (with regular support from and collaboration with faculty) are the habits they will take ownership of and tailor to their own abilities and design habits. Students need to understand clearly that learning by experience and collaboration is a lifelong endeavor, and instruction (or practice in the studio) they receive in the design program is specifically meant to model long-term professional practice.

Liberal faculty-directed practice in the design studio: Student-centered learning in the design studio establishes a model for a professional laboratory; that is, the studio is an open space in which students immerse themselves, establish a presence, and work and experiment in the studio regularly, not simply when an assignment is due. Immersion is important to design skill development, for an environment of experimentation, creative ideas, discussion among students and faculty, and a high comfort level are important to learning what will likely become a very individualized design process for each student. The design studio facilitates the on-going relationship between the student and professor, and effective design processes can be developed during this time. Students learn that an understanding and demonstration of effective design processes determine the ultimate value and utility of a product or process.

Real-world application: Students engage in real-world application of engineering and design through University and community sustainability projects. Projects related to sustainability are endless in nature and scope, and given the opportunity, students often find and develop projects that meet their personal interests and professional aspirations. The School of Engineering also accepts student sustainability projects from all sectors of the local community and the University.

Collaborative design: Assignments in the design program require, at times, that students work independently in order to develop the individual skills and competencies they desire and need. Collaborative work, however, also occupies considerable instructional time and, as well, characterizes a majority of our students' design projects. Successful and rewarding collaborative work requires developing effective communication skills (especially effective listening and conversational skills).

Creative problem solving and idea generation: Design *is* problem solving and idea generation, and more specifically, relies upon successful *assessment* and *evaluation*, whether it be addressing an existing design condition or a flaw (as in redesign), or generating an idea from which a new design may emerge. Instruction in assessment and evaluation for problem solving in sustainability is central to our overall program efforts.

Dispositional assignments: Exercises and assignments in the design sequence are "dispositional", that is, take the form of students practicing and integrating specific design, thinking, and communication skills into their daily lives and activities over the course of the semester. This approach allows students to practice and develop long-lasting and highly useful skills in very personal and real-world settings. In short, such skills rapidly become a part of a student's personality and way of working. As well, this approach saves considerable class instruction time.

Individual Design Process: From our point of view, students can employ a series of design skills they have practiced and "personalized" (adapted to their own thinking and application style, and habits) in order to develop an *individual creative design process* they document in all their studio projects. It is important, however, for students to develop competence in a variety of technical design-related skills including: (1) a familiarity and conceptual understanding of design theory, research, and practice; (2) exposure to theory in materials, construction methods, and product testing; and (3) an understanding of business functions, especially project management.

Problem-Based Learning instruction throughout the curriculum: Much of the instruction in the School of Engineering has been based on a Problem-Based Learning or PBL foundation [60]. For many educators, PBL refers mainly to open-ended problems that incorporate team-based, collaborative learning. At the JMU SOE, however, we have expanded this one-dimensional PBL classification to develop a multi-dimensional PBL model that promotes diverse cognitive experiences. This model is grounded on three dimensions—structuredness, complexity, and group structure. Structuredness pertains to the degree that the learning experience in regards to process (problem statement and problem solving) is defined and structured for the student [60]. Complexity pertains to the degree of challenge posed by the learning activity in regards to the amount and difficulty of domain knowledge students are expected to gain and integrate during the learning experience. Group structure pertains to the varying degree to which students work in a team setting or independently to partake in the learning experience [60]. Varying learning experience characteristics impacts students' cognitive development. Exposing students to a variety of multifaceted problems enables them to experience different modes of thinking, learning, and problem solving. Such cognitive skills are critically important in engineering practice.

7. Assessment and Preliminary Results

To accompany a strong pedagogical model, the School of Engineering has also set forth a detailed assessment plan that continues to improve annually. In fact, embedded in a strong culture of assessment, JMU requires all academic programs to develop an extensive assessment plan and submit annual reports providing evidence of how well students are meeting the program goals. In addition to the JMU assessment culture, three NSF-funded projects (included in the acknowledgements) have also helped shape the assessment practices of the School of Engineering.

The JMU School of Engineering assessment plan includes numerous measures, direct and indirect, to evaluate the extent to which program outcomes are met. The direct measures primarily include seven nationally-used engineering concept inventories (materials, circuits, statics, dynamics, fluid mechanics, thermodynamics, heat transfer), designed to measure students' grasp of fundamental concepts in the engineering science courses. The indirect measures include the National Engineering Students' Learning Outcomes Survey [61,62], a project evaluation survey, achievement goal orientation [63-66], creativity scales [67], and case study and focus group assessment [3,68].

Assessment activities most relevant to the integration of design and sustainability education are the NSF-sponsored longitudinal study assessing student's cognitive development based on Bloom's

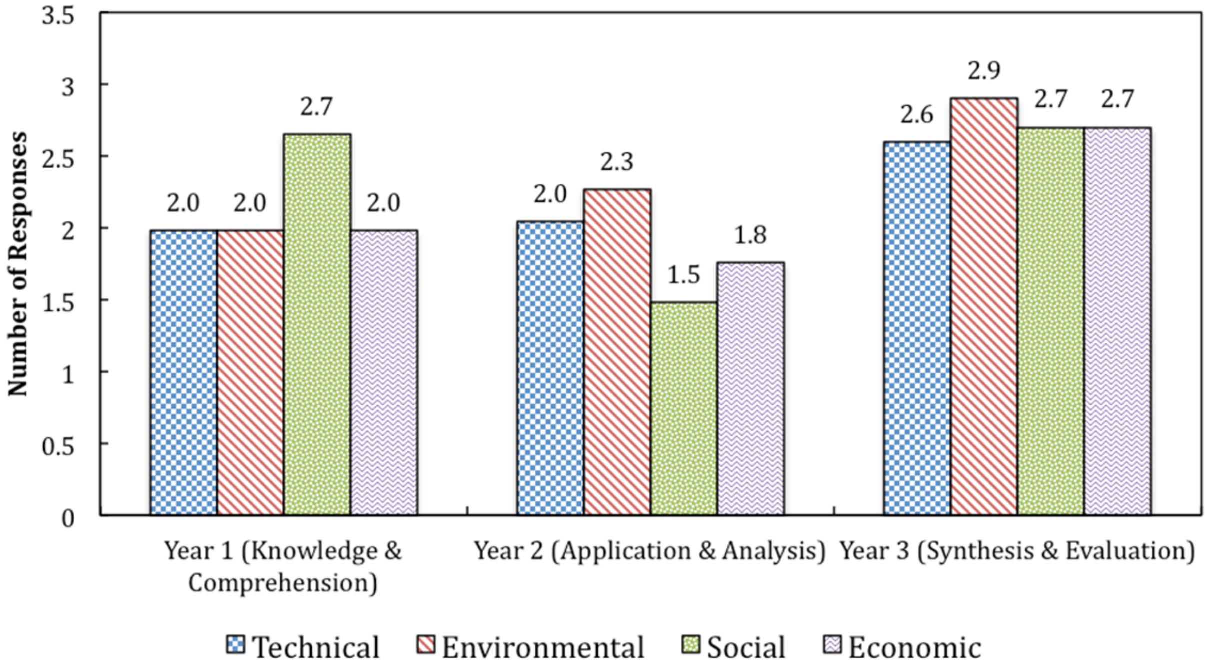
Taxonomy of Educational Objectives [69]. Through the design sequence, we teach students problem solving in four sustainability contexts (environmental, social, economic, technical) using an integrated and developmental methodology employing Bloom's taxonomy [69]. The lower two levels of the taxonomy (Knowledge, Comprehension) require basic thinking skills; as one moves from the lowest levels (on the left, below), the activities require higher level thinking skills. As students become adept at analyzing sustainability case studies, developing and building sustainable designs, and assessing products and processes for sustainability at these two levels, they move on to the next Bloom stages. In short: *Knowledge → Comprehension → Application → Analysis → Synthesis → Evaluation.*

Through this longitudinal study, students, during their sophomore year, junior year, and senior year were given the sustainability case studies (different for each of the three years, but similar in content and complexity). The assessment was a written take-home assignment, time-limited, and low stakes (full credit was given for simple completion of the assignment). During the first year, students were instructed to *identify* and *describe* (and detail, as much as possible) the sustainability issues at stake in each of the four contexts we have been studying (environmental, social, economic, technical). During the second year, the students were instructed to *assess* and *analyze* the sustainability issues at stake in each of the four contexts. In the final year, students were instructed to *evaluate* and make reasonable recommendations related to the sustainability problems at stake in each of the four contexts in the case study. Responses were scored by an engineering faculty with expertise in each particular sustainability context. A score of 0–3 was given to each of the four written responses submitted by each student and was determined by how many valid issues a student identified in each of the four contexts, so that identifying one valid environmental issue in the case study would yield a score of "1" for the environmental sustainability response. In the same manner, if the same student identified three valid social issues in the case study, she or he would score a "3" for the social sustainability response. Each student, then, received a separate score for each sustainability context.

The preliminary results of this assessment are summarized briefly in Figure 2. The students, even in their first year, after just one design course, were identifying valid specific sustainability issues in the case studies at a relatively high rate—averaging 2 of 3 scored responses. Further, we see that as the students progress through the design sequence, they not only begin to look at sustainability issues from a more developed cognitive perspective, but also they identify a greater number of sustainability issues in each case study.

Over the past four years, the SOE's efforts have gained external recognition and support both locally and nationally. Rising juniors and seniors are receiving internships from companies such as Northrop Grumman Corp., Volvo Powertrain, Skanska USA, and Pfizer Inc., and are returning with offers for second internship opportunities and/or full time employment. Rising seniors have taken part in National Science Foundation funded Research for Undergraduate programs at other universities across the eastern United States. Funding is being awarded to student capstone projects (e.g., a campus composting reactor being designed by SOE students funded through the US Environmental Protection Agency P3 program), and our undergraduate students are presenting their work at national conferences such as the Association for the Advancement of Sustainability in Higher Education (AASHE) Conference and Expo. Locally, our students have worked with local industries such as White Wave and Reynolds to gain off-campus work experience during the academic year when internships would otherwise not be feasible. While this evidence is largely empirical, we believe it to be a positive sign toward the overall acceptance of our approach.

Figure 2. Preliminary Results from a Three-year Longitudinal Study Assessing Students' Cognitive Development with Respect to Sustainability Issues in Four Contexts.



Although there are many benefits (for the students and the faculty) to the pedagogical features and curriculum of the JMU School of Engineering, there are also challenges. Some of these challenges include (a) the difficulty of finding appropriate instruments to measure relevant constructs, (b) the challenge of faculty buy-in to integrate our new pedagogical approaches throughout all courses, (c) assuring that student self-assessment is reliable, (d) developing and implementing learning experiences that truly integrate disciplinary learning (amongst engineering disciplines and beyond), and (e) maintaining a common sustainability vision among faculty.

While start-up periods for new academic programs (we are graduating our first students this spring) are normally fraught with organizational and curricular challenges, we are engaged in the following processes: (a) meeting regularly to carefully critique the content and pedagogy in individual courses to determine how well they integrate with the overall curriculum and SOE educational objectives, (b) revisiting the original curriculum plan to insure faculty compliance with the stated school vision, and (c) revising plans for hiring new faculty to insure curricular coverage. In addition, we are carefully mentoring new faculty so they more completely understand the innovative nature of our effort and how they might make a contribution.

8. Conclusions

There are clear motivations for educating students in the manner described in this paper. We would like our students to be innovative, versatile, and creative, and we believe this is best accomplished through designing a curriculum and academic environment that encourages these traits. We consider this simple common sense and good judgment…in fact, good education. In addition, we want our students to be able to negotiate the sometimes treacherous waters of professional practice that include being sensitive to the conditions that promote both human and technological progress, and at the same time, possess a conscience that directs their careers and personal lives. We have included content in our curriculum that focuses on individual values and behaviors, and we expect our students to be good examples of the admirable values they embrace.

We believe that engineers should understand the workings of both the natural and social worlds, and have the abilities and awareness to improve the conditions under which we all live and work. We feel it is important for our students to understand democratic citizenship, professional obligation, and individual responsibility. We understand well the curricular complications of achieving our goals but believe engineers need to be educated in the tradition of the liberal arts as well as engineering, and we have developed and are implementing our curriculum accordingly.

We consider our efforts pioneering and sometimes risky, and it is our hope that others will find value in our approach to judiciously experimenting with engineering education. Our risks are well-considered, and our implementation and methodologies intentional, thoughtful, and based on our own and others' sound research. Our work is being supported by the National Science Foundation, James Madison University, and our substantial research and publications. While we do not eschew traditional approaches to studying engineering, we feel there is significant call to graduate engineers skilled and imaginative enough to face the complex problems we face in our communities, our businesses, and in our global society.

Acknowledgments

The authors would like to acknowledge the support of the National Science Foundation Awards #DUE-0837465, EEC #0846468, and EEC #0933948. The views expressed in this paper are those of the authors and do not necessarily represent those of the National Science Foundation.

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