Infusing Sustainability Principles into Manufacturing/Mechanical Engineering Curricula

Vishesh Kumar, Karl R. Haapala, Julio L. Rivera, Margot J. Hutchins, William J. Endres, John K. Gershenson, Donna J. Michalek, and John W. Sutherland

Department of Mechanical Engineering-Engineering Mechanics
Sustainable Futures Institute
Michigan Technological University
Houghton, MI 49931

ABSTRACT

Sustainability issues are increasingly important among governments, consumers, and corporations around the world. Many companies are directing their resources to reduce the environmental impact of their products and services. In order to remain competitive in the global economy, these companies must recruit employees who understand the impact of their decisions on the environment and society at the same time influencing its bottom line. It is the mission of universities to prepare these future employees to meet this need. A group of faculty and students in the Department of Mechanical Engineering - Engineering Mechanics at Michigan Technological University is working to address this growing demand. This paper assesses the current undergraduate Mechanical Engineering curriculum at Michigan Technological University with regard to sustainability, and identifies barriers to incorporating sustainability throughout the curriculum. A benchmarking study, progress made at Michigan Tech, and a vision for the future of the Mechanical Engineering curriculum are presented.

Keywords: Sustainability, Engineering, Curriculum

INTRODUCTION

The world’s population increased from five to six billion from 1987 to 1999 – a very brief period considering that two centuries were needed for the population to grow from one to two billion [Mogelgaard 1999]. Some projections call for the world population to double in the next 50 years. It should be noted that such projections are made with many assumptions, e.g., lack of large-scale epidemics, stable birth rates, and absence of government intervention. In spite of the fact that some countries such as Japan, Germany, and France have negative population growth, the growth rate in poor countries remains large. Thus, even conservative estimates predict a global population increase of approximately 3 billion in the next 50 years [Cohen 2003].

In addition to the increase in population, developing countries are becoming more industrialized. In the past, increased manufacturing activity has led to per capita increases in resource use and economic activity, contributing to serious environmental problems. The late U.S. Senator Gaylord Nelson from Wisconsin, who pioneered the first Earth Day in the United States in 1970, stressed the importance of the environment to our way of life. “In the jargon of the business world, the economy is a wholly owned subsidiary of the environment. All economic activity is dependent on the environment, and its underlying resource base. If the environment is finally forced to file under Chapter 11 because its resource base has been polluted, degraded, dissipated, and irretrievably compromised, then the economy goes bankrupt with it because the economy is just a subset within the ecological system” [Nelson 1996].

Over the last several decades, many manufacturers have come to recognize the wisdom in viewpoints like that of Senator Nelson and have begun to enact
fundamental changes in the way they operate with respect to society and the environment. In fact, these companies are key drivers for change. For example, Toyota is part of the Earth Institute at Columbia University, which has a Ph.D. program in Sustainable Development [CU 2006]. Toyota is also working with Keep America Beautiful, Inc. to promote a new marketing program for Clean Sweep USA, a web-based environmental sciences education module that helps teachers and students learn about environmental responsibility, recycling, and effective waste management [Clean Sweep 2006]. As the top executive in his organization, Alcan President Travis Engen has declared, “We are working to integrate sustainability into all aspects of our business” [Alcan 2004]. GM, Shell, Alcoa, HP, Dow, and many other manufacturing companies have started to include sustainability initiatives in their annual reports.

There is a growing awareness among manufacturers of the need to consider the triple bottom line (i.e., economic/industrial, societal, and environmental performance) and of the recognition that environmental challenges represent both business opportunities and a societal responsibility. Corporations, governmental agencies, citizens’ groups, foundations, and other non-governmental organizations (NGOs) have shifted focus away from waste treatment and remediation towards energy efficiency, waste minimization, and pollution prevention initiatives. Given the increasing importance of sustainability, it is incumbent upon academia to educate future engineers and other decision makers on sustainability topics, i.e., incorporate sustainability into engineering curricula.

The space race in the 1960s produced a demand for new technology, and a drive for more mathematically- and scientifically-based engineering courses. Engineering programs have continued to evolve during the intervening years [Merton et al. 2001; Schmidt and Beaman 2003]. New courses have been introduced and old courses have changed in order to respond to industry needs. For example, CAD courses incorporate sophisticated software tools and senior design classes make extensive use of team-based efforts. However, several national reports have raised concerns regarding the pace of curricular change, slowness to react to industry needs, and responsiveness to the growing diversity of students [ASEE 1994; NSF 1995; NAP 1995]. Complex administrative systems in universities, inadequate communication links with stakeholders, and the accreditation process itself are some of the reasons for the above concerns.

The undergraduate Mechanical Engineering program at Michigan Technological University (Michigan Tech) is ranked in the top 25 in the nation [U.S. News & World Report 2005]. For over two decades, the program has been one of the largest in the nation in terms of BS degrees awarded. At Michigan Tech, the Department of Mechanical Engineering–Engineering Mechanics (MEEM) oversees the Mechanical Engineering program; MEEM also administers the BSE Industrial Engineering and BSE Manufacturing Engineering degree programs. MEEM is the home of manufacturing education and research at Michigan Tech. Given the intimate connection between the Manufacturing and Mechanical Engineering programs at Michigan Tech, the authors believe that many of the challenges identified in this paper apply equally well to both curricula. Moreover, many of the sustainability related curricular reform issues that relate to Manufacturing/Mechanical Engineering apply equally well to other engineering disciplines.

Michigan Tech has undertaken a new initiative at the graduate level to educate students in the principles of sustainability. Sutherland et al. [2003] reported on the establishment of educational programs in support of a “Sustainable Future” – a sustainable economic/industrial, societal, and environmental future. In the present paper, the authors examine the Mechanical Engineering curriculum at Michigan Tech with an eye toward incorporating sustainability principles throughout the undergraduate experience.

This paper provides a summary of the undergraduate Mechanical Engineering program at Michigan Tech, and the U.S. in general. It describes concerns identified by the authors in preparing students for professional careers in an increasingly complex world, and providing them with the preparation and skills to address sustainability challenges in manufacturing/business.

CONCERNS WITH MANUFACTURING/MECHANICAL ENGINEERING CURRICULA

In order to incorporate sustainability principles and methods into Mechanical Engineering curricula, one must understand the barriers that need to be overcome. In the past, barriers to curricular change have included: i) accreditation focus on “bean counting” as opposed to process improvement, ii) conventional thinking of some faculty members, and iii) company expectations and recruiting trends. While progress has been made in surmounting or reducing some of these barriers, much improvement
is still needed. In this section, the ABET process and the existing curriculum will be reviewed to identify barriers to the inclusion of sustainability. The results of a survey to assess student views of the current curriculum will also be reported.

**ABET Criteria for Engineering Programs**

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. Institutions pursuing accreditation must demonstrate that the program meets a set of general criteria [ABET 2005]. Of particular interest are the requirements of Criteria #2, #3, and #5, which are focused on Program Educational Objectives, Program Outcomes and Assessment, and Faculty. These requirements include:

1. A process based on the needs of the program's various constituencies in which the objectives are determined and periodically evaluated (Criterion #2);
2. The students in the program must attain “an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability” (Criterion #3); and
3. The overall competence of the faculty may be judged by such factors as education, diversity of backgrounds, engineering experience, teaching experience, ability to communicate, enthusiasm for developing more effective programs, level of scholarship, participation in professional societies, and licensure as Professional Engineers (Criterion #5).

In addition, there are specific requirements for an institution that is seeking accreditation of Manufacturing/Mechanical Engineering program. The criteria and requirements act only as guidelines to ensure a certain degree of uniformity among different programs.

Before ABET 2000, which has set the accreditation requirements since 2000, curricula were often driven by a “bean counting” mentality. With ABET 2000, universities and departments are free to formulate program educational objectives and program outcomes, and modify the curriculum to achieve those objectives/outcomes. At Michigan Tech, considerable discussion in the late 1990s resulted in a set of program objectives/outcomes and a continuous improvement “assessment loop” process that ensures an ongoing change in the curriculum to meet the objectives/outcomes [MTU 2005]. In keeping with Criterion #2, virtually all other programs across the U.S. have established similar objectives/outcomes and processes to periodically review and amend program objectives/outcomes. However, the authors are concerned that there is little incentive for programs to amend their goals, objectives, and outcomes. While frequent interactions with constituents occur, and valuable feedback is obtained, the decision to undertake fundamental curricular change carries with it tremendous institutional costs whose benefits may be difficult to characterize or anticipate a priori.

It may seem that the ABET requirements already are addressing the issue of sustainability. Criterion #3 lists the word “sustainability” as part of the general criteria for all engineering programs. From the authors’ viewpoint several of these factors should not be treated as constraints – sustainability is one of those factors. Is ethical behavior a “constraint” or should it be viewed as a philosophy that should permeate personal and corporate conduct? Like ethics, sustainability should not be viewed just as a constraint, but rather as an underlying principle that serves as a key driver in the design of systems, components, and processes.

ABET Criterion #5 requires faculty to show enthusiasm for developing more effective programs. Curricular innovation, however, is not specifically identified as a goal. There is a concern that programs do not embrace curricular innovation, and favor instead tried-and-true curricula. Of course, sticking with what has been done in the past avoids the opportunity for curriculum missteps and over-reactions, but a lack of enthusiasm for curricular change may also lead to staleness and obsoletion. It is believed that at present, most programs too often channel student thinking in traditional directions when solving a problem. For example, meeting personal mobility needs using an automobile, as opposed to telecommuting. New approaches are needed to foster faculty enthusiasm for developing innovative instructional techniques, promote creative problem solving, and nurture unconventional approaches to address societal needs.

Methods used to assess student learning are another area that must be carefully evaluated by universities. ABET requires students to demonstrate mastery in various program areas. However, the ability to connect and integrate knowledge gained in different areas in not emphasized by ABET. This lack of interconnectedness stands contrary to the broader understanding and more system-oriented view that is
required for sustainability. The successful integration of sustainability principles into engineering requires that students achieve an understanding of how various subjects relate to one another and fit into the bigger picture. This will undoubtedly necessitate alternative forms of assessment such as essays, oral presentations, and/or portfolios.

**Course Flow for Mechanical Engineering**

The general course flow for the Mechanical Engineering program at Michigan Tech is shown in Figure 1, and it believed that our curriculum is fairly representative of most other curricula. As can be seen from the figure, the students go through extensive courses in basic sciences, math, basic and advanced engineering principles, and mechanical engineering laboratories in their first three years. They take technical and free electives in their senior year. The curriculum includes general education courses, which focus on humanities and social sciences and develop such competencies as communication skills, teamwork, and ethics. The general education courses are typically expected to address ABET Criterion #3. Often, the engineering/science classes outside of the general education courses largely ignore the issues associated with ABET Criterion #3, and fail to address environmental, social, political, ethical, and sustainability issues.

In the future, engineers will need to apply the principles of sustainability in design and manufacturing. As a result, they will need to be able to evaluate and apply information from a wide range of disciplines including economics, engineering, environmental science, the social sciences, and public policy. In many of these disciplines, there is a considerable level of uncertainty and ambiguity. A successful engineer must 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. For successful integration of sustainability principles and methods into engineering curricula, universities will need to incorporate multi-disciplinary learning experiences and inculcate a higher order of thinking. At the highest stages of thinking, students recognize that all knowledge is contextual and individually constructed [Felder and Brent 2004a, b; Perry 1970]. To achieve this highest level of intellectual development, students not only need the knowledge base to make sound engineering decisions, but they need the cognitive and critical thinking skills to supply effective solutions to technical, environmental, and societal problems.

One potential concern associated with undergraduate Mechanical Engineering curricula is the lack of knowledge integration and limited emphasis on higher orders of thinking. Very few courses actually require students to integrate the knowledge acquired in previous courses. Too often, courses are structured to simply transfer knowledge from the faculty member to the student, with little thought given to helping the student contextualize the material. Of course, expectations vary from instructor to instructor, and those instructors who foster knowledge integration and higher thought should be applauded.

### Figure 1: Course Flow for BSME Degree at Michigan Tech (127 Total Credits; February 2005)

<table>
<thead>
<tr>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fall</strong></td>
<td><strong>Spring</strong></td>
<td><strong>Fall</strong></td>
<td><strong>Spring</strong></td>
</tr>
<tr>
<td>15 Credits</td>
<td>15 Credits</td>
<td>16 Credits</td>
<td>16 Credits</td>
</tr>
<tr>
<td>General Education (3)</td>
<td>General Education (4)</td>
<td>General Education (3)</td>
<td>General Education (3)</td>
</tr>
<tr>
<td>Chemistry (4)</td>
<td>Physics I (1)</td>
<td>Basic Engineering (3)</td>
<td>Basic ME (3)</td>
</tr>
<tr>
<td>Physics I (1)</td>
<td>Physics I (3)</td>
<td>Physics II (5)</td>
<td>Basic ME (3)</td>
</tr>
<tr>
<td>Math I (4)</td>
<td>Math II (4)</td>
<td>Math III (4)</td>
<td>Basic ME (3)</td>
</tr>
<tr>
<td>General Engineering (3)</td>
<td>General Engineering (3)</td>
<td>Basics ME (3)</td>
<td></td>
</tr>
</tbody>
</table>

Number in parenthesis is the credit hours

--- Lab Course

Prerequisite required

No-prerequisite required

![Course Flow Diagram](image-url)
Recently, Wise et al. [2004] found that “curricular changes such as active learning classrooms and team projects can have a positive effect on (intellectual) development, but the advantage does not last without further experiences that support the new modes of thinking.” This suggests that projects, applications, and senior design experiences do promote intellectual development. Time gaps in the curriculum without these types of experiences are to be avoided – active learning must be practiced to be retained.

The importance of the previous observations is that sustainability concepts have not been institutionalized into the Mechanical Engineering curriculum. A few faculty members promote them in a limited number of courses, but there is no integration system-wide. Other concerns are listed below.

- Students are not encouraged to integrate the ideas and concepts learned in their earlier courses.
- Faculty members too often do not utilize examples that help students see the connectivity between courses.
- A sustainability theme (or thread) or even a strong focus appears to be absent from Mechanical Engineering curricula.

It is important to address the problems identified above and find ways to incorporate sustainability into the curriculum. Although these observations are based, in part, on the curriculum and course flow at Michigan Tech, it is believed that these observations are applicable to other Manufacturing/Mechanical Engineering programs in the U.S. and elsewhere around the globe.

**Survey Methodology and Results**

In order to better understand the concerns associated with the present curriculum, a survey was conducted at Michigan Tech to assess the student perception of the ABET requirements, the current Mechanical Engineering curriculum, and sustainability topics. The questions in the survey may be divided into four sections: i) knowledge of ABET requirements, ii) views on the present curriculum, iii) views on sustainability issues, and iv) open-ended questions that sought to identify areas of strength and potential opportunities for improvement. For the first three types of questions, the students were asked to answer whether they strongly agree, agree, disagree, or strongly disagree.

The survey was administered to undergraduate ME students at different stages in their degree program. Out of 112 surveys that were received (~10% of all undergraduate ME students at Michigan Tech), 2 students identified themselves as a first year student, 42 as a sophomore, 27 as a junior, 36 as a senior, 18 as a female, and 73 as a male. The authors tracked additional demographic information of respondents, which is not reported here. It should be noted that for each question there were several students who provided no response.

The results of the survey indicated that on average students recognize that the ABET requirements are essential for their academic program and they strongly agreed that a university should meet these requirements. In terms of the present ME curriculum at Michigan Tech, the results showed that students believe that the University is adequately preparing them for the challenges in the workplace, but that the curriculum does not adequately address sustainability issues. On average, students understand the growing importance of sustainability issues and recognize that the work environment is placing ever more emphasis on these issues.

Some important observations from the survey are listed below:

- The students strongly agree that a Mechanical Engineering (ME) graduate should i) have a solid foundation in basic science, mathematics, and engineering sciences, ii) have the ability to work in a changing environment, iii) have the ability to design useful products, processes, and systems, and iv) have strong problem solving skills. The students also recognized the importance of life-long learning.
- The students were neutral to the fact that an ME graduate should be knowledgeable in the arts, social sciences, and humanities. However, the students felt that societal or environmental consequences were extremely important in the context of making engineering decisions.
- The students indicated that a greater real-world flavor would help them better understand the concepts and theories presented in courses. Additional suggestions were given by the students, which included increasing the level of hands-on experience, more interdisciplinary projects, more laboratory experiences, and more collaboration with industry. Students also identified the need to be sensitive to different learning styles. Connectivity between courses was also a major emphasis in the responses to the open-ended questions. The survey results revealed that students understand the importance of sustainability issues and want sustainability concepts to be institutionalized into the Mechanical Engineering curriculum.
BENCHMARKING

As previously stated, curricular improvements are driven by different factors, e.g., changes in industry trends (hybrid and electric vehicles), changes in technology (microchips and home appliances), and society [NAE 2004]. The increasing emphasis on sustainability is creating a demand for personnel capable of integrating economic, environmental, and societal considerations into engineering solutions. Factors such as regulations (e.g., federal regulations that require a shift from end-of-the-pipe emission treatment to pollution prevention), product take-back, and green manufacturing are creating a demand for curricular change.

As we begin to contemplate a change in the Mechanical Engineering curriculum at Michigan Tech, thoughtful reflection suggests that it would be useful to understand what changes others have undertaken on matters related to sustainability. These changes are related to making the educational system more dynamic, more responsive to changes in technology, more interdisciplinary, etc.

National Science Foundation Initiatives

To address the need for curricular change, federal agencies like the National Science Foundation (NSF) have taken the lead in promoting engineering education innovation by granting funds to universities around the U.S. that are focusing on new and innovative pedagogical topics and methods. A Course, Curriculum, and Laboratory Improvement (CCLI) Program is one of the many efforts at NSF to fund education related topics and methods. The CCLI Program is based on the report “Mathematical Proficiency for All Students” [Ball 2003], and uses a cyclic model (see Figure 2) that describes the relationship between knowledge production and improvement of practice in undergraduate Science, Technology, Engineering and Math (STEM) education. This model also focuses on using results from new teaching and learning methodologies to develop new educational material and delivery strategies.

The CCLI program, as well as several other NSF programs (e.g., CSEMS – CS, Eng. & Math Scholar, and Advanced Technological Education Program), has supported improvements in Mechanical Engineering curricula at many universities. NSF has supported a variety of innovative approaches focused on improving the educational experience provided to students. A summary of some of the proposals that have been funded for Mechanical Engineering curriculum improvement are provided in Table 1. As can be seen from the table, these awards do not focus on improving the overall curriculum in ME. Most of the proposals focus on using computer technology to enhance learning, fostering an industry flavor in a course, establishing an improved laboratory experience, or adopting a greater problem-oriented focus in a course. None of the proposals that were identified addressed the issue of sustainability in the ME curriculum. In fact, the authors were unable to identify any ME curriculum, whether supported by NSF or not, that had a significant sustainability theme/thread within the curriculum.

Initiatives at Other Universities

While we have not identified any Mechanical Engineering programs that have integrated sustainability principles curriculum-wide, there have been initiatives at a few universities directed at implementing sustainability into a course or sequence of courses. Institutions such as Georgia Tech, the University of Washington, Colorado School of Mines, the University of Michigan, Michigan State University, and Michigan Tech have introduced courses with names like Environmentally Conscious Design and Manufacturing, Sustainable Engineering Systems, Alternative Energy Technologies, and Nature and Human Values as vehicles to introduce sustainability into their curricula. At present, virtually all of these courses are technical electives; little progress has yet been achieved in making sustainability part of the required core curriculum. A short description of the some of these initiatives follows.
TABLE I RECENT MECHANICAL ENGINEERING CURRICULUM IMPROVEMENT PROPOSALS FUNDED BY NSF

<table>
<thead>
<tr>
<th>Institution &amp; Award #</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>John Hopkins University (431756)</td>
<td>Emphasis is on increasing and retaining a diverse population, incorporating non-technical topics, creating new courses and modules, and creating a framework to assess changes.</td>
</tr>
<tr>
<td>University of Illinois at Chicago (0354557)</td>
<td>Integration of advanced computing knowledge and techniques by offering computer science courses and establishing a path for specialization in selected topics.</td>
</tr>
<tr>
<td>University of Notre Dame (0080475)</td>
<td>Integration of courses and experiences with microprocessor-based mechanical systems by creating industry oriented courses.</td>
</tr>
<tr>
<td>Rice University (411235)</td>
<td>Implementation of a virtual laboratory using a “haptic paddle” in laboratories to provide students the opportunity to interact with virtual environments to model dynamic systems.</td>
</tr>
<tr>
<td>Kettering University (0310808)</td>
<td>Incorporation of Problem Based Learning into thermodynamic courses by using computer simulations and animations.</td>
</tr>
</tbody>
</table>

Georgia Institute of Technology: The Institute for Sustainable Technology and Development (ISTD) was established at Georgia Tech in 1992 [GIT 2006]. The mission of the Institute is to incorporate the concepts of sustainable technology and development into various curricula at Georgia Tech. The Institute does not develop new courses, and the focus is on adapting existing courses to incorporate sustainability issues. ISTD provides support in terms of research, guidance, and information to help bring about curricular change. ISTD has identified a number of courses in various schools and programs at Georgia Tech and encourages interested students to participate.

University of Michigan: The Center for Sustainable Systems (CSS) was established with the mission to advance the concepts of sustainability through interdisciplinary research and education [UM 2006]. In terms of the curriculum development, CSS has developed environmental sustainability education resources for undergraduate engineers and is working on a hydrogen technology curriculum. The Center also contributes to the undergraduate curriculum through the Program in the Environment, a collaborative effort of the School of Natural Resources and Environment and the College of Literature, Science and Arts.

Some efforts have also been undertaken by universities outside of the United States. For example, the University of Technology, Sydney established an Institute of Sustainable Futures in 1996. The aim of the institute is to conduct research for a sustainable future. However, the educational aspects of the institute are focused on graduate studies as opposed to undergraduate studies [UTS 2006].

We can conclude that there is an increased awareness among faculty and universities to incorporate the concepts of sustainability into engineering curricula. However, most of the efforts have been focused on developing a few courses or developing programs for graduate studies. The next section introduces progress that has been made at Michigan Tech and the vision of the authors in developing a sustainability theme throughout our undergraduate Manufacturing/Mechanical Engineering curriculum.

INFUSING SUSTAINABILITY IN AN ME CURRICULUM

In general, over the last 50 years, the Mechanical Engineering discipline has seen incremental changes in terms of curricula and the way courses are delivered. In the past, mechanical engineering students had a considerable amount of hands-on experience, which provided a strong base for theoretical engineering studies. However, in recent times, this hands-on experience has been lacking, though anecdotal evidence suggests a recent return to a more engineering-practice approach.

One excellent example of an effort to infuse "practice" into the curriculum is the undergraduate Enterprise Program at Michigan Tech that provides an interdisciplinary forum for the solution of state-of-the-art engineering design problems for sophomores through seniors [Plichta and Raber 2001; Stone et al.
2005]. According to the Kolb Learning Cycle (Figure 3) a natural process of learning is one in which individuals first experience the real world and then relate the abstract scientific principles to the real world [Kolb 1984]. Thus, student exposure to more hands-on experiences must be promoted earlier in the degree program.

![Kolb Learning Cycle Diagram]

FIGURE 3 KOLB LEARNING CYCLE

Michigan Tech has established the Sustainable Futures Institute (SFI) to serve as a campus-wide magnet for research, education, and outreach initiatives related to sustainability. Through the SFI, many of the concerns related to a lack of sustainability emphasis in the graduate/undergraduate curricula are being addressed. The SFI is focused on integrating engineering and technology elements of industrial ecology, the scientific elements of environmental assessment and modeling, and the economic and human behavioral elements of the social sciences to support environmental decision-making. The SFI has a significant effort within the Department of MEEM that in addition to research is seeking to incorporate sustainability within the Manufacturing/Mechanical Engineering curriculum.

Several interdisciplinary, sustainability-related courses have been developed and are offered to undergraduate ME students, including Engineering for the Environment, Sustainable Futures I & II, and a Sustainable Futures Seminar, which are offered as general engineering courses, and Life Cycle Engineering and Environmentally Responsible Design & Manufacturing, which are offered through the MEEM department. Although these courses have created some level of awareness among the ME students, they are not required of all students, and no pervasive sustainability theme has been established in the ME curriculum.

The authors believe that more information and real-world learning experience will be required in the curriculum to incorporate a sustainability theme. However, care should be taken and new innovative strategies should be explored so as not to expand the time-to-degree to 5 years. An example is presented in Figure 4, which is presently achievable if students are informed of the appropriate General Education and Technical Electives. Currently, the lower-division general education courses and advanced ME courses do not have a sustainability focus. By implementing sustainability modules in these required courses, a sustainability theme can be readily achieved throughout the ME curriculum.

![ME Course Flow Diagram]

FIGURE 4 ME COURSE FLOW TO INCORPORATE A SUSTAINABILITY THEME
Connectivity for Sustainability

Understanding the role of mechanical engineering also means knowing how society is impacted. For example, air pollution due to poorly designed solutions can impair the health of human beings, flora, animals, and infrastructure [EPA 2005]. Mechanical engineering students should have an understanding of manufacturing by-products, such as airborne particulate, that can harm worker health. Thus, in order to incorporate sustainability principles, the definition of mechanical engineering may need to be redefined to reflect a broader role in benefiting society, promoting economic growth, and preserving the environment. The boundaries that define the mechanical engineering field must be opened to allow interactions with other disciplines and philosophies, thus fostering and strengthening learning from experience and providing a path for the transition into mechanical engineering for a sustainable future (see Figure 5). In addition, a new framework must be established to foster interactions and nurture networking with other disciplines. Examples of disciplines that can provide supplementary knowledge include the social sciences, policy and law, environmental sciences, and the humanities. These interactions will help mechanical engineers to understand their own responsibilities and increase understanding of the role of the mechanical engineering profession in the sustainability equation.

Traditionally, mechanical engineers have been responsible for the design and manufacture of machines and tools, such as industrial machinery. Recently, mechanical engineers have sought to address the needs of society through the development of wind and solar energy devices, computer input-output devices, smart materials, and biomedical devices [Kemper 1995]. For mechanical engineers to assist in societal efforts to reduce and prevent negative anthropogenic impacts on the economy, society, and environment, they must have a solid understanding of the full impact of their decisions. Mechanical engineers must be able to critically assess and improve the products and processes they design and reduce the use of energy and material while increasing the vitality of the environment and society.

An approach to emphasize the inherent connectivity of sustainability is a wholly integrative first-year engineering experience. Courses in humanities, social sciences, and engineering should be entirely intertwined. This can be achieved by relating topics from all areas of academia with a single topic or project. Given the current divisions in academia, the most reasonable approach may be to coordinate activities in several courses to complement each other, perhaps culminating in a final project, which demonstrates comprehensive knowledge in all areas and their integration.

For students to better approach problems, they should be given course work and hands-on experiences that reveal the complexity of situations. For example, learning about internal combustion engines could be coupled with the study of the impacts of automobiles on air quality and assessment of such impacts through life cycle analysis tools. To instill the motivation to help industry and society to become more sustainable, case studies in which such tools have been used in industry to solve complex problems should be discussed. Courses could be designed not only to facilitate an understanding of the connections between engineering decisions, society, and the environment, but also the connections between knowledge gained in other courses and through personal experience.

While all these curricular changes are necessary, the absence of qualified faculty is a barrier to improving the connectivity and infusion of sustainability principles into Manufacturing/Mechanical Engineering curricula. Thus, Manufacturing/Mechanical Engineering departments must recruit and nurture faculty with an understanding of the complexity surrounding the principles of sustainability and a genuine interest in fostering sustainable thinking in students. Faculty should be provided with the resources necessary to successfully guide students toward an awareness of their current and potential roles in the context of a sustainable future. Of course, knowledge of effective pedagogy, relationship building, and mentoring skills are also needed.
SUMMARY AND CONCLUSIONS

It is suggested that the ideas presented in this paper should serve only as a guideline for curriculum development. Ultimately, each university’s culture and educational objectives should be used to establish a vision and scope for its Manufacturing/Mechanical Engineering curriculum or any other engineering discipline. It is the view of the authors that the concept of sustainability is vitally important and should be fully integrated into curricula focused on the design and manufacture of products and systems. It is to be expected that each university will adopt its own approach to making this a reality. The authors believe that the concept and inherent interdisciplinary nature of sustainability aids engineering students in realizing a broader view of the world around them. Infusing sustainability into engineering curricula, including course development and engaged faculty, will provide students with the tools to confront the challenging issues in achieving a sustainable future.

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