TOWARDS MANUFACTURING/MECHANICAL ENGINEERING CURRICULAR CHANGE IN SUPPORT OF A SUSTAINABLE FUTURE

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KEYWORDS
Sustainability, Mechanical Engineering, Curriculum

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 role of their decisions on environmental and societal impacts and influence the 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 and a vision for the future of the Mechanical Engineering curriculum are presented.

INTRODUCTION
The world's population increased from five to six billion in the 1987 and 1999 time period—a very brief period considering two centuries elapsed since the first billion was reached [Mogelgaard, 1999]. In the next 50 years, the world population is projected to double [Cohen, 2003]. Meanwhile, developing countries are becoming more industrialized. Without changes, these factors will lead to per capita increases in resource use and economic activity, contributing to serious societal and environmental problems.

Several years ago, former U.S. Senator Gaylord Nelson from Wisconsin, who pioneered the creation of the first Earth Day in the United States in 1970, commented on 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, more
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. For example, Toyota is part of the Earth Institute at Columbia University, which has a Ph.D. program in Sustainable Development. Toyota is also working with the Keep America Beautiful organization to promote a new marketing program for Clean Sweep USA, a Web-based environmental sciences education module (www.kab.org/cleansweepusa) that helps teachers and students learn about environmental responsibility, recycling, and effective waste management. Alcan President Travis Engen has declared, “We are working to integrate sustainability into all aspects of our business” [Alcan, 2004]. Companies like GM, Shell, Alcoa, HP, and Dow have all started including sustainability initiatives in their annual report.

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. 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 the recognition that environmental challenges represent both business opportunities and societal responsibility. Therefore, it is incumbent upon academia to educate future engineers and other decision makers to address the topic of sustainability in their 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 education shifted away from the traditional laboratory-oriented system; 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.

Michigan Technological University (MTU) 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 this paper, the authors examine the Mechanical Engineering curriculum at MTU with an eye toward incorporating sustainability principles throughout the undergraduate experience.

The undergraduate Mechanical Engineering program at MTU 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 Dept. 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.

This paper provides a summary of the undergraduate Mechanical Engineering program at MTU. 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.

**MECHANICAL ENGINEERING CURRICULUM CONCERNS**

In order to incorporate sustainability principles and methods into the Mechanical Engineering curriculum 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 the section that follows, the ABET process and the existing curriculum will be reviewed to look for sustainability barriers. The results of a survey to assess the students' views of the 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. There are specific requirements that the institution seeking accreditation must fulfill under each Criterion. Some of these requirements are:

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).

The Criteria and requirements act only as guidelines to ensure a certain degree of uniformity among different universities.

At first 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 an operational philosophy? Like ethics, it is the authors' view that sustainability should not just be viewed as a constraint, but rather as an underlying principle that serves as a key driver in the design of systems, components, and processes.

Before ABET 2000, curricula were often driven by a "bean counting" mentality. With ABET 2000, universities and departments were free to formulate program educational objectives and program outcomes, and modify the curriculum to achieve those objectives/outcomes. At MTU, considerable discussion in the late 1990s resulted in a set of program objectives/outcomes and a continuous improvement "assessment loop" process. In keeping with ABET 2000, other universities have established similar objectives/outcomes and processes. The continuous improvement process ensures that there will be ongoing change in the curriculum to meet the objectives/outcomes. In keeping with Criterion #2, we at MTU, and undoubtedly virtually all other programs across the U.S., have processes in place to periodically review and amend program objectives/outcomes as needed [MTU, 2005]. However, we 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/anticipate a-priori.

ABET Criterion #5 requires faculty to show enthusiasm for developing more effective programs, but curricular innovation is not specifically identified as a goal. The ABET requirements for Mechanical (and Manufacturing) Engineering are largely focused on product-based solutions to the needs of society. For example, if society needs a way to get from home to work, the problem is conventionally addressed using an automobile. A non-conventional method of solving the problem may be telecommuting. There is a concern that programs channel student thinking in traditional directions when solving a problem. Efforts are
needed to ensure that our programs foster creative problem solving and non-conventional approaches to address societal needs.

Assessment methods used to test student knowledge is 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. To successfully integrate sustainability principles into engineering, it is important 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. 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 for the first three years. They take technical and free electives in their senior year. A part of the course curriculum is the general education courses, which focus on such competencies as communication skills, teamwork, professional and ethical responsibilities. The courses taken in the general education address ABET Criterion #3.

In the future, engineers will apply the principles of sustainability in design and manufacturing. As a result, new problems will be introduced to solve and apply information from a wide range of disciplines: 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. Successful integration of sustainability principles and methods into engineering curricula requires a systemic change in societal values and high order of thinking and knowledge integration. At the highest stages of thinking [Felder and Brent, 2004a; b; Perry, 1970] students recognize that all knowledge is contextual and individually constructed. To achieve this highest level of intellectual development, students not only need the knowledge base to make sound engineering decisions, they need the cognitive and critical thinking skills to supply effective solutions to technical, environmental, and societal problems.

One potential concern associated with the undergraduate mechanical engineering curriculum 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.

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.

As stated before, the mechanical engineering curriculum typically considers conventional solutions to mechanical/thermal system design and manufacturing. Innovative approaches to problems, and consideration of environmental and social effects of conventional solutions is too often missing from courses.

The importance of the previous observations is that sustainability concepts have not been institutionalized into the mechanical engineering curriculum. They are promoted in a few courses by a few faculty members, but there is no integration system-wide. Other concerns are listed below.
- There is a lack of connectivity between courses. Students need to be encouraged to
integrate the ideas and concepts from multiple courses.

- Faculty members too often do not utilize examples that help students see the connectivity between courses.
- We are not aware of a mechanical engineering curriculum that has a sustainability thread running throughout it. 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 course flow at MTU, it is believed that these observations are applicable to most other mechanical and manufacturing engineering programs.

Additional suggestions included increasing the level of hands-on experience, more interdisciplinary projects, more laboratory experience, and more collaboration with industry. Students also indicated that they would like to more connection between courses, more sensitivity to differences in learning styles, and more real-world applications. The survey revealed that the MTU students did recognize the importance of environmental and societal issues.

**BENCHMARKING**

As stated before, curricular improvements are driven by different factors, e.g., changes in industry trends, changes in technology (like micro-chips, hybrid and electric vehicles, and home appliances), and society [NAE, 2004]. The increasing emphasis on sustainability is creating a demand for personnel capable of integrating economical, environmental, and societal considerations into an engineering solution. Considerations 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 MTU, 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.

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 ways of
teaching. NSF created the Course, Curriculum, and Laboratory Improvement (CCLI) Program. 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.

![Cyclic Model for Knowledge Production and Improvement of Practice in Undergraduate STEM](image)

**FIGURE 2 CYCLIC MODEL FOR KNOWLEDGE PRODUCTION AND IMPROVEMENT OF PRACTICE IN UNDERGRADUATE STEM [NSF, 2005]**

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 national 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 2. As can be seen from the table, these awards do not focus on improving the overall curriculum in mechanical engineering. Most of the proposals focus on using computer technology to enhance learning, fostering an industry flavor in a course, establishing an improved laboratory experience, and 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 thread with the curriculum.

<table>
<thead>
<tr>
<th>Institution &amp; Award #</th>
<th>Description</th>
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<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 (0354567)</td>
<td>Integration of advance computing knowledge and techniques by offering computer science courses and establishing a path for specialization is 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 &quot;haptic paddle&quot; in laboratories to provide students the opportunity to interact with virtual environments to model dynamic systems.</td>
</tr>
<tr>
<td>Kettering University (0310806)</td>
<td>Incorporation of Problem Based Learning into thermodynamic courses by using computer simulations and animations.</td>
</tr>
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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. Universities such as Georgia Tech, Univ. of Washington, Colorado School of Mines, 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 the their curricula. At present, virtually all of these courses are technical electives; little progress has yet been achieved in making sustainability part of required curriculum core.

**A VISION FOR THE MTU ME CURRICULUM**

As described above, the mechanical engineering education system 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 this change is the undergraduate Enterprise Program at Michigan Tech that provides an interdisciplinary forum for the solution of practical engineering design problems for sophomores through seniors [Plichta and Raber, 2001]. According to the Kolb Learning Cycle (see 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.

FIGURE 3 KOLB LEARNING CYCLE

The weak connectivity between basic science and math courses with mechanical engineering courses must also be addressed, possibly by rearranging the course flow. More experiences and opportunities are needed where students can learn and apply knowledge and techniques to real-world problems. Since it appears likely that more information and learning experiences will be added to the curriculum, innovative strategies should be explored so as not to expand the time-to-degree to 5 years.

One approach to emphasizing 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 of all areas and their integration.

Traditionally, mechanical engineers have been responsible for the design and manufacture of machines and tools, for example, industrial machinery. Recently, other applications like wind and solar energy devices, computer input-output devices, smart materials, and biomedical devices have emerged [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 they design and the processes used to manufacture those products to reduce the use of energy and fossil fuels in the face of increasing materialization.

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, fauna, 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 4). 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 public policy, environmental engineering, and the social sciences. 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.

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 are 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.

FIGURE 4 MOVING FROM A CLOSED TO AN OPEN FRAMEWORK

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.

To summarize and conclude, it is suggested that the vision that has been outlined serve only as a guideline. Ultimately, each university’s culture and educational objectives should be used to establish a vision and scope for its mechanical/manufacturing engineering curriculum. It is the view of these 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. Finally, the authors believe that the concept and inherent interdisciplinary nature of sustainability forces students to accept a broader view of the world around them, which in turn will cause students to adopt a higher level of intellectual development.

REFERENCES


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