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DIFFUSION OF SUSTAINABLE SYSTEMS ENGINEERING THROUGH INTERDISCIPLINARY GRADUATE AND UNDERGRADUATE EDUCATION AT THE UNIVERSITY OF MICHIGAN

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ABSTRACT

This paper provides specific examples of sustainability education programs within the engineering curriculum at The University of Michigan at Ann Arbor (UM). These programs exist at the undergraduate, Masters, and Ph.D. levels of education. At the undergraduate level, a basic literacy program has been initiated to give each graduating mechanical engineer from UM the understanding required to make design decisions less impacting on the environment. The program is designed as an educational thread consisting of three (3) course modules corresponding to each of three required courses in the Design and Manufacturing sequence in the mechanical engineering department. To compliment the thread, a new joint course between mechanical and environmental engineering in *Environmentally Sustainable Engineering* is under development to serve as the cornerstone undergraduate course in environmental education for the UM College of Engineering (CoE). At the Masters level, the ConsEnSus (Concentrations in Environmental Sustainability) Program is described. This program has been introduced to enhance general environmental literacy and to prepare students to integrate environmental principles into professional practice. Similarly, a joint Ph.D. program has also been developed between CoE and the School of Natural Resources and the Environment to prepare students for a career in research and education related to sustainable engineering. Both ConsEnSus and the Ph.D. program are supported by a course entitled *Principles of Eco-Design and Manufacturing*. This course, and the graduate and undergraduate programs it supports, is part of a college-wide effort to make Sustainable Systems Engineering a reality in practice by disseminating operational definitions of sustainability targeted to specific engineering disciplines.

1. INTRODUCTION

While the ***conceptual*** definition of sustainability offered by the Brundtland Commission has enjoyed widespread support over the past fifteen years, sustainable engineering principles have only to a minor extent diffused into actual consumer products, manufacturing processes, and societal infrastructure systems. To accelerate the diffusion of these principles, it is necessary to develop ***operational*** definitions for the design of sustainable engineering systems. Operational definitions are essential to the sustainability movement as they are ***discipline-specific*** and compatible with traditional engineering education and practice. Once discipline-specific operational definitions of sustainable engineering principles are established, it will be essential to develop compatible education programs that can facilitate their dissemination within engineering curricula at all levels. Efforts to develop such curricula at the University of Michigan at Ann Arbor (UM) are the topic of this paper.

While environmental education and research is one of the fastest growing areas in academia, discipline-specific education, taught from a context-specific sustainability framework, is largely absent from engineering curricula. At most American universities, a wide array of courses is available to analyze the consequences of human interaction with specific environmental media and to describe engineering methodologies to control or remediate anthropogenic pollution. A growing number of universities are now providing elective courses introducing specific sustainability methodologies such as life cycle analysis [1], design for environment [2], and industrial ecology [3,4]. A number of these efforts have evolved into full programs of research and education which address important concepts at the interface between engineering and the environment. Such programs include the program on Environmentally Benign Design and Manufacture at Georgia Tech [5], the Green Design Initiative at Carnegie Mellon University [6], the program on Multi-Life Cycle Engineering at the New Jersey Institute of Technology [7], and the MIT Center for Technology, Policy, and Industrial Development [8]. Although such programs provide numerous educational

	Topics in Lecture	Supporting Computer-Based Exercise
Design and Manufacturing I	Motivation for Environmental Protection Introduction to Pollutants Engineering "Cause-and-Effect"	Vehicle Emissions Impacts on Ann Arbor
Design and Manufacturing II	Material and Energy Balances Eco-Efficiency Metrics EcoDesign Trade-offs	Develop a Design for a Chair
Design and Manufacturing III	Life Cycle Assessment Open-Ended EcoDesign Experience	Apply EcoDesign/LCA Concepts to Open-Ended Design Problems

Table 1. Structure and Content of EcoThread for Design and Manufacturing Courses Under Development at UM.

resources related to environmental sustainability, it can be argued that universal integration of environmental issues has not yet occurred within mainstream undergraduate and graduate mechanical engineering programs. This objective would be facilitated by greater availability of design and manufacturing oriented case studies and exercises, the integration of environmental science examples to physical science courses (e.g., teaching global warming concepts in a basic heat transfer courses, teaching ozone depletion in a general chemistry course, etc.), and a greater commitment to environmental education at all levels of mechanical engineering curricula.

This paper provides specific examples of sustainability education, based upon operational approaches, within the engineering curriculum at UM. The structure and content of three discipline-specific sustainable engineering education programs are described. These programs exist at the undergraduate, Masters, and Ph.D. levels of education. At the undergraduate level, development of an environmental thread has been initiated to give each graduating mechanical engineer from UM the basic education required to understand how to make design decisions with less environmental impact. This undergraduate sustainability thread is discussed in Section 2. In Section 3, a new course entitled ***Environmentally Sustainable Engineering*** is described that provides intensive undergraduate education in sustainable engineering. The course is meant to serve as a general Cornerstone educational experience that can feed in to graduate-level sustainability courses specific to individual disciplines. One such graduate course, entitled ***Principles of Eco-Design and Manufacturing***, is described in Section 4. This course serves to provide operational approaches to sustainability specific to mechanical engineering. *Principles of Eco-Design and Manufacturing* is also one of three core courses in the ***ConsEnSus*** program described in Section 5. ConsEnSus (Concentrations in Environmental Sustainability) is a Masters level degree concentration program that has been designed to give students the opportunity to pursue a Masters of Science in Engineering (MSE) degree in a traditional engineering discipline coupled with advanced study in issues of environmental sustainability. Section 6 describes a joint Ph.D. opportunity for engineers interested in interested in placing fundamental engineering research within a broader legislative and policy framework.

2. ECO-DESIGN AND MANUFACTURING THREAD

As mentioned above, a long term goal has been established to give each graduating mechanical engineer from UM the basic education required to understand how to make design decisions with less impact on the environment, and to use the environment as an inspiration for creative design and leaner manufacturing. For this goal to become a reality, environmental science and thinking must be systematically integrated to the ME curriculum, such that accounting for environmental impact will ultimately become a natural part of decision-making. Unfortunately, the Accreditation Board for Engineering and Technology (ABET) does not currently provide specific guidance regarding how to include such environmental content in engineering curricula. As a result, environmentally benign design and manufacturing (EBDM) content has rarely progressed from elective courses to required courses within ME programs in the U.S. Considering the widespread issue that most ME programs have "too many required courses" already, it cannot be expected that environmental education for engineers can be addressed by converting elective EBDM courses to required courses within the undergraduate curriculum. Consequently there is a need for novel course modules covering basic EBDM concepts that can be seamlessly integrated into existing design and manufacturing courses.

Toward this end, there is an Eco-Design and Manufacturing thread under development at UM that consists of three (3) course modules which correspond to each of three required courses in the Design and Manufacturing sequence in the ME Department (Design and Manufacturing I, II, III). As shown in Table 1, these modules consist of lectures, supporting problem sets, and Internet-based educational resources. The modules also feature integration of EBDM concepts within laboratory and design projects. The three modules are described in the following paragraphs.

EcoModule 1: Design and Manufacturing I. Design and Manufacturing I is a 2^{nd} year undergraduate required course which covers basics of mechanical design and manufacturing such as visual thinking, engineering drawing, and machine anatomy. Topics such as manufacturing processes, materials, and computer aided design and manufacturing (CAD/CAM) are introduced. The environmental module being developed for this course offers a commensurate basic-level introduction to air and water pollution in the context of engineering decisions. This introduction is spread over two lectures. Lecture 1 describes the basic environmental issues, along with some discussion of incentives and inhibitors to environmental improvement via prevention. Lecture 2 describes specific examples of air, water, and land pollution resulting from manufacturing processes and engineered consumer products. The moral behind the specific lessons of the lectures is that Mechanical Engineering decisions have a fundamental "cause and effect" impact on the environment. The cause and effect of

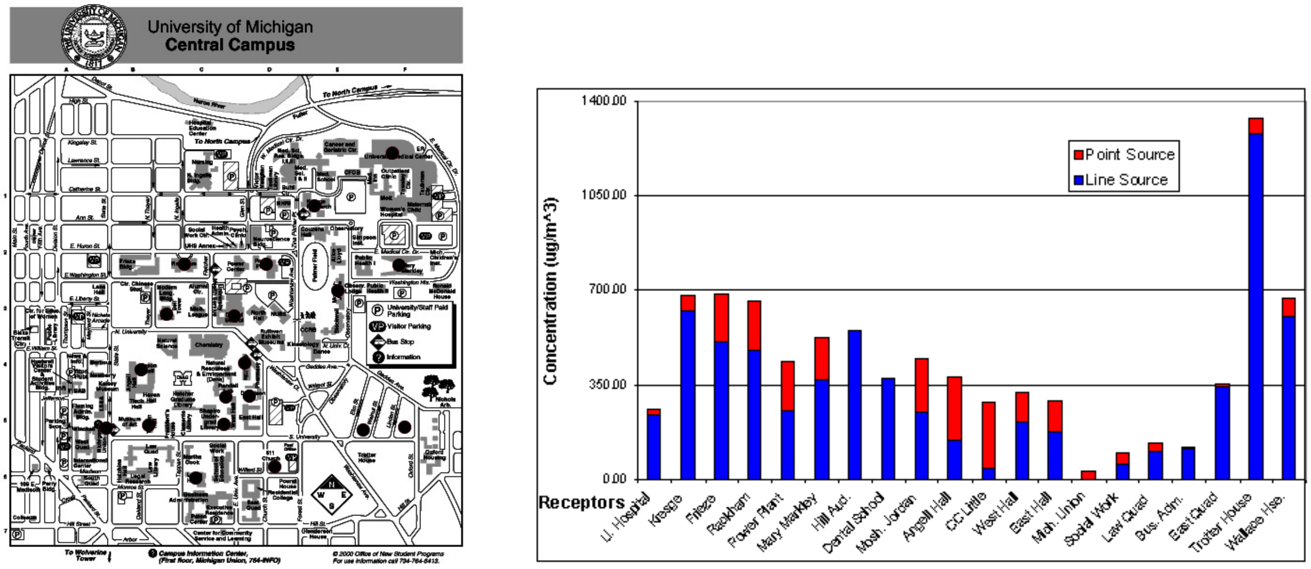

Figure 1. (Left) Central campus streets and locations considered for contributions to air pollution. (Right) Carbon monoxide air pollutant concentrations due to line sources at 20 central campus locations.

ME decisions is demonstrated in numerous case studies presented, ranging from automobiles to cell phones. The theme is intended to motivate students to investigate the environmental impact of engineering choices as part of their chosen career.

Supporting reading material is to be provided on the Internet at a website called "DFE World" (described below). On the website, there is an interactive homework exercise for Module 1 called "Impacting the Central Campus Air Quality". The main objective of the assignment is for the students to develop an intuitive understanding of the cause and effect of engineering decisions through a demonstration of how vehicle emissions impact air quality in the city of Ann Arbor. A web-based model was developed that incorporates calculations from the EPA supported *California Line Dispersion Model* [9]. The model provides a reasonably accurate model for the UM Central Campus that predicts the air quality contributions from road sources at 20 locations in Ann Arbor as shown in Figure 1. Air pollutant concentrations from mobile sources are accounted for by using Year 2000 traffic volume data on 20 major streets on Central Campus.

The model allows students to alter emissions characteristics of vehicles, either by changing powertrain technology or fuel composition. Impacts of weather conditions, traffic density, and vehicle composition are also considered, providing an opportunity to explore system-level and situational aspects of EBDM. After completing the exercise, the students 1) have a working understanding of the benefits of low emissions vehicles to air quality, 2) gain a basic understanding of air quality modeling using line and point sources, and 3) understand the meteorological and urban planning factors that affect air pollutant concentrations at different locations. They also gain a real and tangible understanding regarding how improved mechanical engineering design can lead directly to the improvement of environmental conditions.

EcoModule 2: Design and Manufacturing II. Design and Manufacturing II covers advanced mechanical design and manufacturing, including synthesis and selection of machine components. Building off of the introduction to sustainability issues provided in Module 1, Module 2 intends to provide intermediate-level coverage of 1) material and energy balances, 2) metrics of eco-efficiency, and 3) environmental trade-offs in design and manufacturing. A lecture has been developed that covers these topics in the context of life cycle assessment and the environmental evaluation of products and processes.

To support the lecture, students will be provided a set of Product Life Cycle tutorials on the DFE World website. Specific issues in material selection, manufacturing, packaging, transportation, product use, and product end-of-life are specifically covered. Metrics for measuring environmental improvement are also reinforced within a homework exercise for Module 2 where students are asked to perform a cradle-to-grave design for a simple chair as illustrated in Figure 2. With this exercise, students are provided actual life cycle assessment (LCA) information for different materials that can be used to produce a chair (e.g., wood, plastic, metals, etc.). The students can specify materials, manufacturing methods, transportation methods and distances, and end-of-life scenarios. Energy and environmental emissions are tracked throughout the design to provide students experience with evaluating design concepts in the context of an interactive example. The example is set up such that while the students have creative freedom, there is enough supporting information to permit reasonable environmental evaluation (i.e., the uncertainty in the example is relatively low, since the students do not have to worry about data quality or missing data). As a complete "ready-made" LCA such as this would not usually be available for concept evaluation under a real-world design situation, open-ended EcoDesign and life cycle model building are discussed in EcoModule 3.

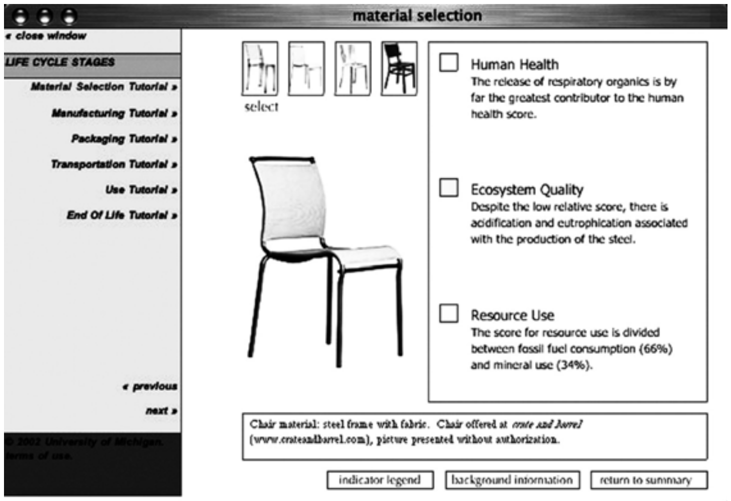

Figure 2. Example of Environmental Considerations in the Design of a Chair from DFE World.

EcoModule 3: Design and Manufacturing III. This is the capstone design and manufacturing course in the ME curriculum. The educational goal of the course is to give each student a deep understanding of how to approach open ended mechanical challenges *by process*, and to teach him or her how to creatively catalyze, synthesize, and apply the seemingly fragmented engineering knowledge acquired during their undergraduate studies to the design and manufacture of real mechanical systems. This is achieved through an open-ended design project which exposes students to the full design and manufacturing process from concept to prototype.

The environmental module for this course challenges students to apply pollution prevention and design for environment strategies to their open-ended design and manufacturing projects. Students are held accountable for applying EBDM concepts to their prototype development, analysis, and final reports. Life cycle assessment databases to support evaluation of project concepts are provided to the students in order to facilitate this process. One example is illustrated in Figure 3. In this example students were re-designing the housing of two cellular telephones to facilitate disassembly and remanufacturing for sale in emerging markets. While the bulk of the student effort focused on fixturing and geometrical issues in the housing, the students also applied EcoDesign concepts to the materials selected for the housing. The students recognized that under a re-manufacturing scenario, it would sometimes be necessary to replace the housing of the incoming cell phone. To replace worn or damaged housings, they envisioned the use of biodegradable materials that would not contribute to landfill or increased CO_2 emissions (by incineration). Figure 3 is one possible solution developed in partnership between engineering students at UM, and fellow industrial design students at the Parsons School of Design (New York). Naturally, such environmentally conscious variants of their senior design projects must be evaluated by the students for sales potential, economics, and robustness.

DFE World DFE World is a website under development where students can find supporting resources and exercises related to the EcoModules. In addition to resources discussed above, two JAVA applications are under development for web-based access of environmental impact data on the website. First is the so-called "Environmental Nutrition Label" shown in Figure 4 (Left), which intends to provide quantitative impressions of the environmental impact of engineering materials and processes, with the added intuitive impressions carried by a familiar aesthetic. The label also intends to 'hook'

Figure 3. Sample eco-design of Cellular Telephone Housing (Parsons School of Design and University of Michigan). (Left) Bio-based soya resin concept for cell phone housing. (Right) Steps to recover cell phone circuit board and compost the bio-degradeable housing lined with seeds.

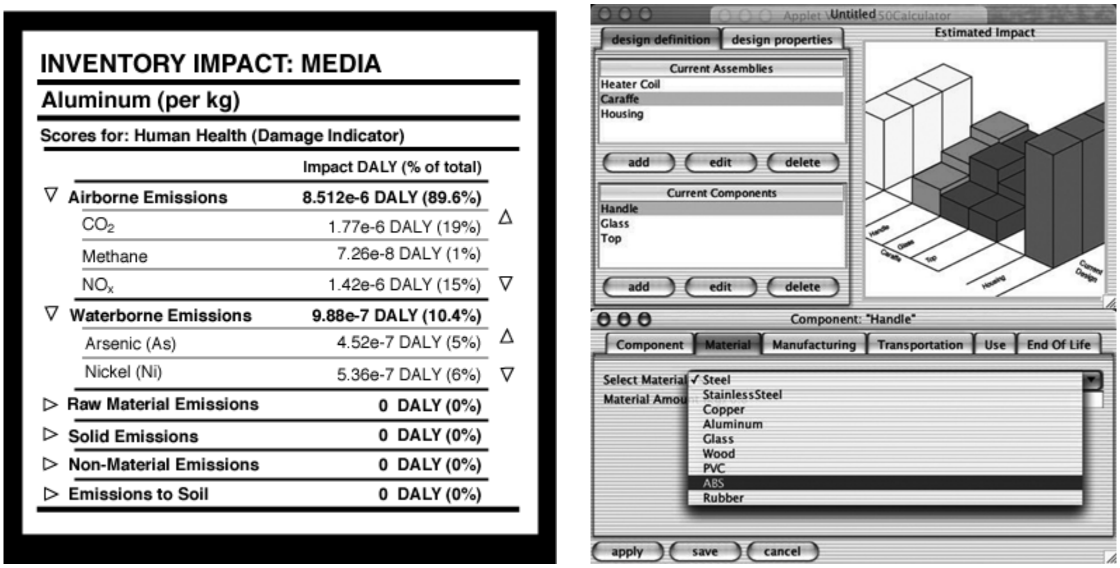

Figure 4. Tools under development in DFE World (coffee maker example shown). (Left) Summary information based on the EcoIndicator 99 method. (Right) Calculator accruing environmental releases associated with design changes.

students into exploring these characteristics within a unique and familiar framework for the communication of supplemental product information. Students are able to select materials or processes and receive a multi-tiered report of scalable environmental impact scores. Naturally, students must be informed regarding the approximate nature of all databased environmental metrics, and therefore students are repeatedly informed about situational aspects of eco-metrics, and dangers of “oversimplification” of environmental product evaluation.

In addition to the label, a calculator has been developed (for EcoModules 2 and 3) which allows students to enter in a heirarchical definition of their designs in terms of components and assemblies defining geometry, materials, processing, and assembly techniques. With each alteration of the design, the impact of the design, represented by a familiar bar graph, is ‘pushed’ onto a sequence of similar graphs created by previous designs (Figure 4 Right). Keeping this history of designs not only allows for semi-quantitative evaluation of the design in terms of environmental impact, but also allows the students to comprehend and investigate the drivers for increases or decreases in impact. Consequently, students can explore how different materials and methods change the environmental characteristics of their designs.

Summary: EcoDesign and Manufacturing Thread. By providing this environmental sustainability education “threaded in” to the Design and Manufacturing sequence at UM, it is intended that students will eventually treat environmental and sustainability issues as a natural part of all engineering decision-making, similar to quality and safety considerations. However after participating in the EcoDesign and Manufacturing thread, it is not expected that students will be environmental experts. In fact, it is stressed that the students are little more than exposed to important environmental issues. They are educated enough to understand their importance, and to determine which environmental issues are important for a design they are involved with. “Places to go” for more learning and consultation on unique projects are stressed, and it is expected that students have the ability to “ask the right questions” to learn more about the environmental consequences of design and manufacturing processes under their influence.

3. ENVIRONMENTALLY SUSTAINABLE ENGINEERING

The goal of this course is to serve as an introductory undergraduate engineering course that will teach fundamental sustainable engineering principles. The course will: (1) serve as a key core course for the environmental engineering program within Civil and Environmental Engineering (CEE), and (2) serve as a core course for CEE, Mechanical Engineering (ME) or any other College of Engineering (CoE) departments interested in developing an undergraduate concentration in Sustainable Engineering Systems.

While design for environment concepts are beginning to trickle down into the CoE undergraduate curriculum via specialized graduate-level electives, sustainable engineering principles have yet to be integrated in a comprehensive and systematic way within any single engineering department at UM. It is critical for this to occur at the undergraduate level, since the majority of UM graduates enter practice without taking graduate level courses and therefore miss any deep introduction to sustainable engineering principles.

To meet this demand, *Environmentally Sustainable Engineering* is a course under development by the authors. The course is initially expected to be cross-listed between CEE and ME. Quantitative aspects include evaluating environmental fate, hazard, and risk of environmental pollutants. They also include the development and manipulation of sustainability metrics for engineering systems based on mass balance, physical-chemical properties, transport relationships, and LCA.

The following areas will be covered during the course:

1. Environmental regulation, economics, and sustainability;
2. Chemical properties/fate and transport in air, land, and water;

3. Materials hazard, risk assessment, and environmental impact;
4. Metrics for sustainable systems engineering;
5. Energy, Energy Alternatives, and the Environment;
6. Sustainable Mobility;
7. LCA and environmental costing of green design;
8. Other broad EcoDesign case studies in civil, mechanical, electrical, chemical, and energy systems.

With these topics covered in a single course, *Environmentally Sustainable Engineering* will serve as a general Cornerstone educational experience that can feed in to graduate-level sustainability courses specific to individual engineering disciplines. These courses would provide operational sustainability approaches that are discipline-specific. One such graduate course, entitled *Principles of Eco-Design and Manufacturing*, is described in the next section.

4. PRINCIPLES OF ECODESIGN AND MFG.

This full-semester course has been developed for undergraduate and graduate students interested in advanced coverage of environmental issues prevalent in materials extraction, manufacturing, product use, and end-of-life within the metals, plastics, and semiconductor industries. The mission of the course is to provide the conceptual, methodological, and scientific bases to understand and reduce the impact of mechanical engineering design and manufacturing practices on the environment. The course serves as an introduction to chemical, physical, and biological systems important to understanding pollution generation and its prevention through improved design and alternative manufacturing processes.

Course Overview. *Principles of EcoDesign and Manufacturing* (PEDM) is organized into four interconnected sections. Section 1 establishes the urgency for a new approach to environmental protection based on prevention, and provides interactive forums (*roundtables*) for student engagement into a discussion of motivators, drivers, and inhibitors to environmental protection. Section 2 covers life cycle assessment with a focus on manufacturing processes. Metals, plastics, and electronics manufacturing technologies are covered along with environmentally conscious process alternatives and energy sources. Section 3 provides a quantitative introduction to the basic science of environmental impact assessment, covering the modeling of global warming, smog formation, ozone depletion, acid rain, eutrophication, and oxygen depletion. Section 4 covers design strategies, case studies, technologies, and metrics for making environmentally benign engineering decisions. These sections of the course are elaborated in the following paragraphs.

Section 1. Section 1 of *PEDM* provides motivation, perspectives, and background on environmental and sustainability issues. Since *Environmentally Sustainable Engineering (ESE)* has not yet been taught, there is significant overlap between Sections 1 and 3 of *PEDM* and topics covered in the *ESE* course. For instance, regulations, economic incentives, and inhibitors to sustainable design and manufacturing are specifically covered in both courses. Specific air, water, and land pollutants are also introduced in both courses. The major difference between this section of the course and what is covered in the *ESE* course is the volume, depth, and level of reading. *PEDM* includes philosophical and technical discussions of society, technology, and economics based on a selection of the 1000 page coursepack of readings compiled uniquely for this course. Rather than straight lecturing, much of this material is taught and reinforced in the context of roundtable discussions. This is because by the time they reach *PEDM*, many students have spent significant time working in industry. Their experiences provide an ample reservoir of content to discuss sustainability issues as they relate to corporate activity, and the roundtables provide opportunities to tailor the course examples to student interests.

Section 2. Section 2 begins with a rigorous introduction to life cycle assessment (LCA) concepts. Students learn how to conduct life cycle assessments, and how to think critically regarding the quality of an LCA that they review. After an introduction to LCA, the students learn about specific sources of pollution in manufacturing. They also learn about environmentally benign manufacturing principles and technologies. For metals manufacturing, primary metals production, foundry operations, forming and machining, cleaning, and finishing are all covered. LCA database information for primary metals production is described explicitly, along with known pollutants and sector notebook data for manufacturing, cleaning, and finishing. Environmentally benign manufacturing technology is described in detail such as net shape casting, solid free form fabrication, dry/damp machining, lubricant and cleaner recycling, powder coating, etc. The life cycles of electronics products, including semiconductor and printed wiring board production, are also described. Similarly, the environmental and performance characteristics of plastics, recycled plastics, and bio-based plastics are discussed.

Section 3. Section 3 introduces the transport and impacts of environmental pollutants discussed in Section 2. A cause-and-effect introduction to pollution impacts such as greenhouse gas forcing, smog, ozone depletion, and oxygen demand are provided in the context of systems modeling. Students are educated in developing basic mass balance models that include chemical reactions and conversions. This education is developed through in-class examples, homework problems, and exams. Two quantitative examples are provided as modeling homework assignments covering 1) air pollution from multiple smokestacks in a city, and 2) water pollution due to several paper mills on a river. These small team projects serve to reinforce and support the lectures on transport modeling and environmental impacts.

Section 4. The science-based introduction to environmental impact provided in Section 3 allows Section 4 to begin by describing metrics of sustainability and environmental impact. Commonly utilized metrics such as EcoIndicator 99 [10], EDIP [11], and MET [12] are compared and contrasted with respect to their strengths and weaknesses. Life cycle inventory data and environmental metrics are used to evaluate designs of products such as refrigerators, television sets, automobiles, and other consumer products. EcoDesigns for these products are also discussed. During Section 4, a small-team reverse engineering exercise is also performed (during lecture). The students are provided access to available LCA databases to help them understand the functional decomposition and environmental impact of products they bring in from home. The students present these issues, along with possible environmentally conscious re-designs of the products to the rest of the class. The semester concludes with a final roundtable which summarizes and synthesizes the learning objectives of the course.

Teaching Methods. A number of student teams have developed novel web-based resources that have been used as intergenerational peer-to-peer teaching tools. For instance, students have produced educational resources related to bioplastics, air pollution, and automotive emissions that have been integrated with the course website. All term projects are required to either 1) develop new knowledge in the EcoDesign and Manufacturing field, or 2) improve access to existing EcoDesign and Manufacturing knowledge by producing effective educational resources. Therefore the term projects emphasize both content and effective communication, and they are graded against the criterion of suitability for release to a public forum. Artifact-based education has also been introduced to the class in order to improve teaching effectiveness. For instance, instead of lecturing on metals manufacturing processes in isolation, the topic is discussed (along with eco-alternatives) in the context of manufacturing a refrigerator. Similarly, plastics and electronics manufacturing processes are described in terms of manufacturing a television. Dozens of such concrete examples are used to teach EcoDesign processes. By attaching product and process-based artifacts to environmentally benign design and manufacturing concepts, it is expected that the students will better learn the material and be able to apply it to their day-to-day activities after graduation.

5. ConsEnSus

The ConsEnSus program was developed by the curriculum committee of the UM College of Engineering Institute of Environmental Science Engineering and Technology (IESET) and put into practice in 2000. The program is designed to augment a traditional Masters of Science in Engineering (MSE) degree with advanced study in issues of environmental sustainability (http://www.engin.umich.edu/prog/consensus/). The ConsEnSus Program requires completion of twelve credits of coursework related to the topic of environmental sustainability within an MSE program in one of five participating CoE departments. The completion of the program is certified and marked on university transcripts in accordance with other concentrations available in the College of Engineering (e.g., Concentration in Manufacturing Systems).

Five of the twelve credits necessary for ConsEnSus certification are required courses. The first three credits can be obtained by taking *Principles of EcoDesign and Manufacturing* or *Industrial Ecology* (crosslisted course between the Department of Civil and Environmental Engineering and the School of Natural Resources and the Environment). The remaining two required credits are obtained by taking *Case Studies in Environmental Sustainability* (cross-listed course between Chemical Engineering and Civil and Environmental Engineering). This course is designed to be a forum of interaction between students and real-world engineers involved with sustainability projects. The format of each class is set up such that a real-world sustainability “problem” is presented to the class at the beginning of each lecture. Rather than a one-way lecture regarding the sustainability solution the practicing engineers devised, the students are required to interact toward developing their own solutions. The solution development is mediated by the course instructor and visiting lecturer. The semester concludes with presentations of term projects which require the students to identify a relevant case study in industry and perform an economic, societal, and environmental impact assessment. Students are also expected to generate recommendations for improvement with respect to these issues.

The remaining seven credit hours of the ConsEnSus concentration may be selected from a list of courses approved by IESET and the participating CoE departments. Courses are divided into three categories: 1) Environmental Law and Regulations, 2) Environmental Assessment and Policy; and 3) Environmental Science and Technology. At least two of the categories must be represented in the selection of the seven elective credit hours.

Currently, the ConsEnSus program is set up to provide concentrations in five CoE MSE departments:

- Atmospheric and Oceanic Space Sciences
- Civil and Environmental Engineering
- Chemical Engineering
- Mechanical Engineering
- Naval Architecture and Marine Engineering

The program has a director (Professor Walter J. Weber, Civil and Environmental Engineering) along with supporting advisors within each department offering the concentration. The advisors assist in student consulting and in verification of meeting both departmental and ConsEnSus requirements.

6. SNRE / ENGINEERING JOINT PH.D. PROGRAM

It has become increasingly recognized that there is a need for analysts and researchers at the Ph.D. level with a fundamental understanding of policy development and technology system design to support industry and government in decision-making related to the environment. The need for educational initiatives to address this interface between policy and engineering is evidenced by the success of programs such as the Engineering and Public Policy program at Carnegie Mellon University [13] and the Institute for Environmental Science and Policy at the University of Illinois at Chicago [14]. At UM, the following abilities were identified as important in the delivery of joint policy and engineering education at the Ph.D. level:

- Perform fundamental discipline-specific engineering research
- Understand data source issues related to decision-making
- Identify root-causes of policy issues
- Analyze complex systems
- Understand design of engineering systems
- Perform impact analysis for engineering decisions

To instill these skills at the Ph.D. level, a degree has been developed between the UM College of Engineering and the UM School of Natural Resources and the Environment (SNRE) with the aim of providing fundamental knowledge of engineering design and its relationship to environmental, economic, political, and social systems. The program also intends to provide a fundamental understanding of where engineering design and policy decisions intersect, how they impact one another, and what feedback mechanisms exist to ecological, social, and industrial systems. At the conclusion of the program, a student should have the analytical tools to critically assess decisions, evaluate impacts, and analyze trade-offs quantitatively as well as qualitatively in a socio-economic and political context. The degree is believed to provide a basis for dialogue, and the common vocabulary and skill set necessary, to achieve mutual understanding across disciplines.

The joint SNRE / CoE degree is individually tailored to the specific research questions under investigation by the applicant. The requirements mirror university requirements for a Ph.D., with the inclusion of an advisor from both CoE and SNRE. To date, one student has graduated from the program. The specific research investigation involved related to the development and life cycle analysis of petroleum and bio-based metalworking fluid emulsion systems utilized in manufacturing [15, 16].

7. CONCLUSIONS

This paper has described educational initiatives related to sustainability education for engineers spanning the undergraduate, Masters, and Ph.D. levels of education. Due to the "overfull" nature of the undergraduate curriculum, an educational thread in EcoDesign and Manufacturing is currently under development for the UM Department of Mechanical Engineering. The thread is designed as three (3) course modules corresponding to each of three required courses in the Design and Manufacturing sequence in the mechanical engineering department. To compliment the thread, a new joint course between mechanical and environmental engineering in *Environmentally Sustainable Engineering* (*ESE*) is under development. This course will serve as the cornerstone undergraduate course in environmental education for the whole UM College of Engineering (CoE). Both the environmental thread and *ESE* will be supported by a web-based resource environment called DFE World.

At the Masters level, the ConsEnSus (Concentrations in Environmental Sustainability) program has been developed, and so far two mechanical engineering students have graduated. One has found employment in the Thailand government as an environmental health industry advisor. The other student now works in the Environmental Quality office at Ford Motor Company. These initial data points indicate that the program has the potential to generate skill sets relevant for sustainability decision-making in the real world. Similarly at the Ph.D. level, a joint program between the UM College of Engineering and the UM School of Natural Resources and the Environment has been developed to provide fundamental knowledge of engineering design and its relationship to environmental, economic, political, and social systems. The first graduate of this initiative now serves as a program analyst at the Environmental Protection Agency in Washington D.C. This also suggests the relevance and viability of interdisciplinary engineering programs at the Ph.D. level for producing students capable of driving real world sustainability initiatives.

8. ACKNOWLEDGEMENTS

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