# A Sustainability Indicators based Curriculum

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## Abstract

The United States Environmental Protection Agency (EPA) release the report entitle "A Framework for Sustainability Indicators at EPA" which describes how information may be utilized to provide data from the economic, environmental and social sustainability information into a single composite variable that attempts to measure sustainability in two or more of the categories. The framework report provides a list of single parameter sustainability indicators and a template for using rational multi-parameter indexes as a means to making decisions on sustainability based upon measureable information. The course ENGR 412 Sustainability Engineering and Design II was developed to introduce students to multi-parameter sustainability indices, such as global warming potential, footprint analysis, and concepts in life-cycle analysis. The goal of the course is to provide foundational tools to expose all engineering students in the department to evidence-based methods of making sustainable decisions in engineering design. This paper describes the evolution of the evidence-based sustainability curriculum.

## Keywords

Life Cycle Assessment, GREET, Sima Pro, Scope, Inventoy analysis

## Background

Sustainability is important in manufacturing, construction, planning and design. Alleby *et. al*. state that: "Sustainable engineering is a conceptual and practical challenge to all engineering disciplines.[1]" The concepts of sustainability have often been pigeonholed into graduate level courses in Industrial Ecology or Green Engineering.[2] Environmental engineering and chemical engineering textbooks may cover some basics concepts of sustainability, but the extent and breadth of knowledge is insufficient to meet the multifaceted demand associated with engineering sustainable processes and products.[3]

Crittenden suggests that sustainable solutions include the following important elements/steps: (a) translating and understanding societal needs into engineering solutions such as infrastructures, products, practices, and processes; (b) explaining to society the long-term consequences of these engineering solutions; and (c) educating the next generation of scientists and engineers to acquire both the depth and breadth of skills necessary to address the important physical and behavioral science elements of environmental problems and to develop and use integrative analysis methods to identify and design sustainable products and systems.[4]

The Association for the Advancement of Sustainability in Higher Education (AASHE) compiles data for programs that identify sustainability focused curriculum, as shown in Table 1.[6] In spite of the large number of existing programs, there is no consensus yet as to the curriculum requirements for implementation of sustainable design practices across undergraduate engineering programs.[7] Davidson et. al reported roughly 155 engineering courses with a focus on sustainable engineering, only about 50% of which were mainly focused on sustainability concepts. The sustainability sequence described herein introduces applications of fundamental environmental science and sustainability indicators that are being broadly adopted by industry and organizations to make informed resource management and design decisions.

Table 1: Self-identified sustainability-focused programs listed by AASHE in 2013[8]

| Level/degree of the program | 2013 | | 2015 | |
|---|---|---|---|---|
| | Number of programs | Engineering programs | Number of programs | Engineering programs |
| Associate Degree | 30 | 4 | 33 | 3 |
| Baccalaureate Degree | 417 | 63 | 430 | 61 |
| Joint Degree | 34 | 1 | 34 | 1 |
| Specialization/Concentration/ Emphasis | 17 | 2 | 17 | 1 |
| Minor | 146 | 14 | 149 | 14 |
| Undergraduate Certificate/Diploma | 48 | 7 | 54 | 7 |
| Graduate Certificate/Diploma | 135 | 10 | 137 | 7 |
| Masters Degree | 448 | 84 | 476 | 84 |
| Doctoral Degree | 103 | 59 | 105 | 59 |
| Post-Graduate Certificate/Diploma | 32 | 1 | 35 | 1 |

The EPA has also incorporated sustainability principles into its mission. Sustainability was defined by Executive Order 13514 “to create and maintain conditions, under which humans and nature exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations” (NEPA[1969; EO.13514). The National Academy of Sciences (NAS) report defined a Sustainability Framework and a Sustainability Assessment and Management approach for the EPA in 2011. This approach includes sustainability screening, scoping and options identification, scoping and application of sustainability tools and tradeoffs/synergy analysis. The NAS report specifically relates social impacts to health risk issues as well as using a range of “sustainability tools” that consider social justice issues and consider risk assessment when developing sustainability management principles.

The engineering curriculum at James Madison University is an ABET accredited general engineering program with a focus on sustainable design principles. The engineering program has developed a two-course sequence of sustainability-focused courses focused on the engineering applications of sustainability science, environmental impact analysis, and applications of models of sustainability, such as Green Building analysis and Life Cycle Analysis (LCA). The two-course sequence was developed to address the mission statement of the department:

*Department of Engineering graduates will improve the sustainability of our world by analyzing problems and designing solutions in the context of technical, economic, environmental, and social impacts.*

The first course "ENGR 411: Fundamentals of Sustainable Engineering and Design" focused on introducing general sustainability concepts and quantifying environmental impacts. The second course, "ENGR 412: Sustainable Engineering & Design II" focused on material and energy balances and life cycle assessment. The two-course sustainability sequence includes foundational knowledge of environmental impact assessment methods, life cycle analysis, and energy considerations. Prerequisites for such a course are the foundational math courses in calculus, chemistry, and physics. The sustainability sequence was designed for sophomore to senior students in engineering and is applicable to all engineering disciplines.

There is a tremendous range of courses offered in sustainability related fields, often due to a professor's singular expertise or interest.[8,9] The authors of this sustainability-focused curriculum have drawn on their various backgrounds in engineering, policy and technology to assemble a comprehensive curriculum on sustainable design and development. Understanding sustainable design and related fields like basic climate science, green building and life cycle analysis will continue to gain importance for practicing engineers and scientists. This sustainability-focused curriculum introduces a new approach to sustainability that includes foundational knowledge of environmental impact assessment methods, life cycle analysis, and energy considerations that are being adopted in many accredited engineering and technology programs. The sustainability-focused curriculum applies engineering principles to real-world design and problem analysis. It includes specific step-by-step examples and case studies for solving complex problems that appear throughout the two courses. Both courses utilize conceptual and applied problems at various levels of difficulty. Both courses also apply the principles of sustainable design to issues in both low-income and high-income countries.

The specific topics covered in the ENGR 412 course include:

- Models for Engineering Sustainable Design
- Energy Conservation and Development
- Industrial Ecology
- Life Cycle Analysis
- SimaPro LCA Modeling
- Engineering for Human Communities: The Social Context of Sustainable Design

This paper discusses the experience and challenges in adapting Life Cycle Assessment processes in an undergraduate general engineering course, ENGR 412. The expected course outcomes and related ABET criteria associated with each course are listed in Table 2. Senior-level General Engineering students took the sustainability-focused curriculum described in this study. The topics covered are discussed and framed below.

Table 2. Expected outcomes and related ABET criteria for sustainability-focused courses

| Outcome ID | Course | Expected Course Outcomes | Related ABET Criteria |
|---|---|---|---|
| 1 | 412 | Perform calculations involving conventional units utilized in engineering | a, e |
| 2 | 412 | Prepare mass balance equations to track materials flows in manufactured products and emissions | a, e, h |
| 3 | 412 | Solve mass balance problems related to impacts of industrial processes | a, e, h |
| 4 | 412 | Identify criteria for evaluating social considerations in sustainable development | f, g, h, j |
| 5 | 412 | Describe the relationship between global, regional and local environmental impacts, and economic factors | f, g, h |
| 6 | 412 | Predict and feel concern for the biological and environmental effects of the design of man-made devices | f, h |
| 7 | 412 | Develop frameworks for conceptualizing complex, open system problems, and the inter-relationship of environmental, energy, economic, health, technological, and cultural factors | b, c, e, g, h, i |
| 8 | 412 | Implement sustainability tools, such as life cycle assessment when conducting systems analysis | a, c, h |
| 9 | 412 | Model total material cycles (i.e. product cradle-to-grave life including design, manufacturing, and disposal phases) when developing products and processes | a, h |
| 10 | 412 | Use professional software to perform a basic life cycle assessment | e, h, i, k |

**Models for Engineering Sustainable Design**

This course module discusses definitions of sustainable development through international case studies centered around sustainable development success stories in sub-Saharan Africa, including documentary video of the work of the Songhai Center in Porto-Novo, Benin directed by Namujo Godfrey and the restoration work in Kenya developed by Professor Wangari Maathai.

Footprint-base sustainability indicators such as the ecological footprint, water footprint, carbon footprint and nitrogen footprint are introduced as quantities measures of sustainability principles that can be applied to resource and waste management.

**Energy conservation and development**

Students in this module are introduced to energy equity issues through on-line documentary videos that discuss Clean Cookstove appropriate technology. Students then utilize carbon footprint and global warming potential sustainability indicators to quantitatively compare energy generation processes. A discussion of direct and embodied energy provides a segue to industrial ecology concepts and Life Cycle Analysis functional units are introduced.

## Industrial Ecology

Student engage in a discussion of the IPAT (Impact = Population x Affluence x Technology) equation, it uses and limitations. The concept of intergeneration equity is discussed after students have reviewed TED (Technology, Entertainment and Design) talks on intergenerational equity and resource allocation. The social dimension of sustainability discussion is transitioned to a discussion of carbon emissions and quantitative analysis of countries emissions based upon their energy portfolio and global warming potential. The concepts of health risk assessment are also introduced and students are required to perform simple EPA based health risk assessments as part of the EPA's method of quantifying social sustainability. The complexities and limitation of risk assessment and other preceding material provide a framework for developing and interpreting Life Cycle Analysis (LCA) in the following module.

## Life Cycle Analysis

Approximately six weeks of the course was devoted to Project-Based Learning (PBL) based approach to Life Cycle Analysis (LCA). The PBL and case study based approach to incorporating this approach to adopting systems thinking and sustainability concepts in the curriculum supported by Dym et al. (2005). LCA is introduced early in the semester to allow students additional time to become familiar with LCA software (GREET and SimaPro). The ISO 14044 LCA framework of *Goals, Scope and Definition*, *Inventory Analysis, Impact Assessment and Interpretation* is introduced. The concept of a functional unit is also introduced. Students then go through the process of deconstructing a case study based upon a published palm oil LCA to develop an understanding of ISO framework.

## SimaPro LCA Modeling

Students are assigned a term-based LCA project to complete using appropriate software (GREET or SimaPro) for the second half of the course. Substantial course time is dedicated to teamwork, software instruction and peer-assistance and review of the LCA work. Existing on-line tutorials and tutorials developed by the software companies were used for the students to learn basic application principles with class-time spend trouble shooting software questions for two to three periods.

One lesson learned in developing the course content, was that students had great difficulty developing the connections and content required to properly utilize available software packages. The prerequisites for changed for the course to require students to have senior standing to enroll in the course and have completed most of the engineering sciences prior to enrolling in the ENGR 412 class. Additionally, an introduction to systems engineering course (ENGR 413) is typically taken as a co-requisite or prerequisite to the ENGR 412 course. A basic knowledge of systems analysis that includes framing problems, identifying variables, and understanding uncertainty is helpful when describing the Inventory Analysis, Impact Assessment and Interpretation of LCAs. In this course, case studies based upon hemp production and footwear production were used to illustrate the inventory analysis and LCA framework, students were then asked to work in peer groups to develop an inventory analysis and framework for a student-focused case study. The students were then asked to share their results, with peer-suggestions for improving the inventory and framework, and finally the faculty instructor provided an example solution for the case study.

## Engineering for Human Communities: The Social Context of Sustainable Design

The final week of the course involves discussions about the limitations of sustainability indicators discussed throughout the course. The diffusion of technology and economics of sustainability are also discussed in an open forum and are again based upon on-line/textbook case studies such as the Jaipur Foot and Millennium Development Goals success stories.

## Student Feedback

Evaluation of the course provided student feedback that will be used to continually improve the course. Students reported that the footwear and hemp production case studies were helpful, particularly for understanding the goals and scope of an LCA. Students reported that it would be helpful to introduce the LCA software earlier to allow more time to learn and practice with the software. Students also reported mixed results utilizing existing on-line tutorials. Students requested “mini-assignments” that might help them break down the LCA process. Students were in agreement that the nature of the course was conducive to team-based projects, as they were able to learn the software and share the learning experience.

## Summary

ENGR 412 has been offered since 2010 and various modifications, improvements and redesigns have been introduced to the syllabus based on feedback from student evaluations and teaching assessment polls as well as identified weakness in students’ abilities. The most significant course modifications include:

- The time spent on the materials and energy flow analyses modules was increased in order to teach algebraic functions and techniques as this was previously observed to be deficient and a hindrance to proper appreciation of life cycle impact analysis methods.
- On-line course materials were developed to introduce sustainability concepts and provide greater context through on-line video documentaries that provide coverage of social, economic and environmental interactions. Professors provide guided discussion related to the triple-bottom line of sustainability.
- The Life Cycle Assessment module originally focused solely on one LCA software package and instruction in specific software assignments in SimaPro. Students proved capable of utilizing the software, given detailed guidance for inputs to the program, however, students had difficulty interpreting the development of the framework for LCA and also had difficulty interpreting results. As a result, more course time is dedicated to developing LCA scope and inventory analysis. The Argonne GREET Model has also been added to the teaching schedule to allow students to become more comfortable with selecting LCA modules related to a framework they develop.
- The module on energy flow and efficiencies is related to thermodynamic laws covered in ENGR 311 and ENGR 312 which are the departmental thermal sciences classes. The material taught in ENGR 412 has been designed to help contextualize the lessons form the introductory courses and deepen the understanding of the role of thermodynamics in sustainability. Due to this change, ENGR 311 and ENGR 312 are now prerequisite courses for ENGR 412.

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