AC 2011-2528: INTEGRATING SUSTAINABILITY INTO SYSTEMS ENGINEERING CURRICULUM

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Integrating Sustainability into Systems Engineering Curriculum

Abstract

"We do not inherit the Earth from our ancestors, we borrow it from our children." This quote, often referred to as an ancient Native American Indian proverb, summarizes the principle of sustainability: meeting the needs of the present without compromising the ability of future generations to meet their own needs (Bruntland[1]). The importance of sustainability becomes clear as we try to meet the constantly increasing needs of our society with limited resources on Earth. Systems Engineers can play a very important role in this, that is why, at the Systems Engineering and Engineering Management Program of University of North Carolina at Charlotte, we are looking for ways to incorporate sustainability into the curriculum.

The purpose of this study is to provide a preliminary road-map for Systems Engineering programs for curriculum design to incorporate sustainability into their curriculum. As part of this process, our specific objectives are 1) to identify learning objectives and topics, and 2) courses and levels of courses where sustainability and sustainable design can be taught. A brief summary of sustainability curriculum practices at different institutions is also provided.

Some of the possible sustainability topics that are considered in this research are life cycle assessment, alternative energy sources, principles of sustainability, greenhouse gases, carbon footprint, energy audits, design for sustainability, managing systems based on triple bottom line (environment, economy and society), reverse logistics, and sustainability metrics for continuous improvement. For courses and their levels, we are considering the options of either creating a new course entirely dedicated to sustainable system design and/or hosting relevant topics in some of the relevant existing courses. Some of these potential courses being evaluated for sustainability integration include SEGR 2101 (System Engineering Concepts), SEGR 3101 (System Design and Deployment), SEGR 4131 (Product and Process Design). Our preliminary findings based on benchmarking of other programs indicate that while some engineering and business fields offer a more extensive sustainability-related curriculum, there is still a growth opportunity for systems engineering programs in the area of sustainability and sustainable design.

Introduction and Motivation

Today's global environmental crises such as global change, ozone depletion, overpopulation, acid rain, air and water pollution, limited water resources or loss of biodiversity make it clear that our current management of nature's resources is not something that is sustainable in the long run. If we want to satisfy the needs of future generations, we have to manage our current and limited resources much better than we have done it in the past.

It was the UN World Commission on Environment and Development (the Brundtland Commission, report named *Our Common Future*[1]) in 1987 that suggested that sustainable development was necessary to meet human needs while not increasing environmental problems. A move toward more sustainable living emerged, including increasing public awareness of the situation and adoption of recycling, and renewable energies such as wind and hydroelectricity.

By the dawn of the 21st century sustainability and environmentally conscious behavior finally became "mainstream".

Sustainability can be defined in terms of its three dimensions, often referred to as the three pillars of sustainability: environmental, social and economic (also known as people, planet and profit). In other words, sustainability is not only looking at the environmental aspects and consequences of our actions but also making sure that society's needs are fulfilled while businesses remain profitable. Often these seem to be three conflicting dimensions but it is possible to create sustainable developments where a business can create value for customers, investors, and the environment, and a sustainable business is able to meet customer needs while, at the same time, makes profit and also treats the environment well. But to meet the triple bottom line, a multidisciplinary cooperation is necessary to understand the integrated "whole" of these different systems. Cooperation between scientific, social and economic disciplines, public and private sectors, academia and government is unavoidable to make these cross-disciplinary efforts successful.

Sustainable or green businesses have to find green alternatives that function at the same or a better level and possibly at a lower cost while taking into account the entire life cycle of a product. Examples of achieving these goals might include reviewing processes to eliminate or recycle waste, making all products recyclable, or eliminating the use of nonrenewable resources via alternative energies. Sustainable businesses can chose to go paperless, conserve materials through remanufacturing, convert harmful gases into clean energy, generate greener power or try to improve fuel economy. They should also establish a long-range sustainability strategy and environmental policy. A different kind of design principle will also have to be applied: sustainable design. It will need to be purposefully employed in all areas of life: design of any object or product or service has to be in line with the three pillars of economic, social, and ecological sustainability. As this is an integrated design process that demands cooperation from many different sides of the design team, the role of systems engineering and engineering management to oversee these projects becomes extremely important.

This is why today's systems engineers will have to have a great understanding of sustainability and how the triple bottom line could be and should be met for every project. They need to understand many different principles of sustainable design, for example, how to use low-impact materials that are non-toxic, sustainably-produced or recycled materials; how to be energy efficient and use manufacturing processes and produce products which require less energy; how to make products that have high quality and more durable, so they last longer, thus being replaced less frequently to minimize their replacement; how to design for reuse and recycling, so they are not going to be discarded after their "first life" is over; how to measure carbon footprint and make life-cycle assessment of products, just to name a few examples.

While today's generation is probably the most educated about environmental issues and has concerns about the environment, it is still not enough. As Bridges and Wilhelm[2] point out, "a recent content analysis of principles of marketing textbooks found that of the six leading textbooks, an average of only 3% of each text includes some coverage of sustainability issues (Demoss & Nicholson [3]). Where present, coverage is primarily limited to general strategic discussions about the importance of being aware of environmental issues and/or tactical decisions about product materials or production processes (e.g., use of recyclable materials)." So there seems to be still a long way to go in terms of incorporating sustainability into curriculums.

The purpose of this study is to provide a road-map for Systems Engineering programs for curriculum design to incorporate sustainability into their curriculum. As part of this process, our specific objectives are 1) to identify topics, 2) courses and levels of courses where sustainability and sustainable design can be taught 3) while also summarizing some of the sustainability curriculum practices at different institutions. This paper is organized as follows: after a literature review of current issues of sustainability in education, a benchmarking of selected institutions is provided with a focus on learning objectives for sustainability education. Finally, these findings are connected to the program and courses currently being taught at the University of North Carolina at Charlotte (UNC Charlotte) to see how this program can be enhanced, followed by a discussion and conclusions.

Literature Review

While there are many papers that are worth mentioning in the literature for sustainability education for engineers, we have to limit this paper to a few highlights only. For example, in 2000, Crafton[4] posed the question about what kind of changes were needed in the curriculum to have adequately prepared engineers for the challenges of sustainable development and to increase the effectiveness of their solutions. There are many authors who tried to answer that question.

Examples of general courses and programs that documented sustainability education in the past decade include Coulsen and Thomsen[5], who described learning activities, delivery mechanisms and assessment processes in an Accounting and Sustainability undergraduate course at Strathclyde University in Scotland. The work of Bridges and Wilhelm[2] suggested how marketing education should incorporate sustainability into their curriculum, the role of sustainability in marketing strategy, and the implementation of an MBA-level marketing elective course, while Wheeler et al.[6] looked at several eLearning models and examined two case studies with eLearning for education for sustainability applied to formal K–12 settings, higher education, learning in the workplace or business sector, and also community-based continuing education. More examples include Goodnough et al.[7], who presented an overview of the sustainability initiatives at the University of Minnesota, Morris, such as a new environmental studies curriculum, and various research and outreach projects.

MacDonald[8] described how educating for sustainability is done in Manitoba including "policies that integrate sustainable development concepts into provincial curricula, establishing sustainability indicators and reporting on indicators, developing regulations and policies that work towards greening operations of educational institutions, and supporting educators in the Field". They concluded that there is a need for "strategic, systemic, and concerted action to support educators as they work to develop students' knowledge, skills and values that contribute to a sustainable future". They also supported that the use of systems thinking as a practical and pedagogical framework would be a way to go in that direction as "the systems concept can help students to see how they are part of larger entities and how these larger entities include natural and manmade environments in a more encompassing whole. [..] and "systems thinking can help students appreciate the complexity and tensions behind sustainability-related issues and provide frameworks and tools for developing and implementing solutions."

Boks and Diehl[9] described the challenge of integrating sustainability issues into a regular industrial design engineering product innovation course. Instead of just requiring students' assignments to show how sustainable product concepts can be incorporated to a traditional business, they tried to put sustainability into a bigger picture, where, for example, social issues such as safety play a role with the hope that this gives not only a better motivation and enthusiasm to students and teachers but the better motivation also leads to a better learning process.

Focusing more on sustainability in engineering and management, Porter & Cordoba[10] described three views of system theories and their implications for sustainability education to extend the notion of systems thinking as it pertains to sustainability pedagogy. The authors developed three broad approaches to systems thinking: functionalist, interpretive, and complex adaptive systems (CAS), which resulted in a practical set of ideas and pedagogical tools for immediate adoption by management educators in any field. Rusinko & Sama[11] worked on "Greening and Sustainability Across The Management Curriculum", describing the journey across time, disciplines, programs, and sectors, while Stables[12] raised the question whether education for environmental sustainability is possible through creativity, and explored three different contexts: in design and technology schools (where teenage learners are being facilitated to develop creative responses within design briefs that include environmental considerations); through interviewing student teachers who have undertaken an eco-design project; and through interviews with professional eco-design practitioners. He also suggested an eco-design capability approach for taking forward creativity and environmental sustainability in technology education. Borchers et al.[13] gave a detailed example of an undergraduate course in environmental design and manufacturing, while Lynch-Cary and Sutherland[14] discussed how to integrate principles and practices of sustainability into the industrial engineering curriculum.

Kumar et al.[15] discussed infusing sustainability principles into manufacturing and mechanical engineering curriculum and describing challenges of the process and a benchmarking study at Michigan Tech. They concluded that the three main barriers were lack of accreditation process improvement, conventional thinking of some faculty members and company expectations and recruiting trends. Christensen[16] investigated how deans and directors at selected 50 global MBA programs respond to questions about the inclusion and coverage of the topics of ethics, corporate social responsibility, and sustainability at their institutions. In terms of sustainability they found that one third of these schools require all three topics as part of the MBA program, and there is a trend toward the inclusion of sustainability-related courses. Also, that several of these schools are teaching these topics using experiential learning and immersion techniques.

The World Resources Institute and the Aspen Institute annually publishes a list of the top 100 full-time MBA programs that integrate environmental and social content into the curriculum (see website at http://beyondgreypinstripes.org/rankings/index.cfm). According to this website, "The top disciplines, in order, teaching about social, environmental and ethical issues are: 1. Management, 2. Finance, 3. Marketing, 4. Corporate Social Responsibility (CSR)/Business Ethics, 5. Accounting".

The literature review showed that there are multiple examples of sustainability courses and programs indifferent engineering and non-engineering fields, but examples of sustainability curriculum are limited in systems engineering and related fields. Thus we do hope that this paper will be a step addressing that need.

Sustainability in Systems Engineering Education

In this section, we provide a summary of the current state of sustainability education at the systems engineering degree programs in US. The list of systems engineering academic programs has been obtained from the International Council on Systems Engineers[20]**.** Table 1 below summarizes our findings about these programs and the current state of their sustainability-related coverage based on the program and university web pages.

As seen in this table, out of the 47 programs 13 of them offer a BS degree in Systems Engineering, 41 of them offer an MS and 14 of them offer PhD degrees in Systems Engineering. The web research showed that sustainability coverage is relatively rare in systems engineering programs: It seems that none of the systems engineering undergraduate programs offer sustainability-related courses. There are four institutions which offer courses at graduate level (1. Boston University, which offers ENG SE 543 - Sustainable Power Systems: Planning, Operation and Markets, 2. MIT, which offers a Leadership Lab: Leading Sustainable Systems, 3. University of Southern California, which offers ISE 576 - Industrial Ecology, and 4. University of Virginia, which offers SYS 6070 - Environmental Systems Analysis). Out of the 13 undergrad degree offering institutions, two of them have minors (1. George Mason University, where a sustainability minor is offered by the Science College and 2. University of Pennsylvania, where a minor on Energy and Sustainability is available) and another one has a degree in sustainability (Washington University in St. Louis, which offers a BS in Sustainability at the Arts & Sciences College). Out of 41 graduate degree offering institutions three of them have concentrations (1. Cornell University, which offers a track on Sustainability Systems Engineering, 2. George Mason University, which offers a concentration on Energy and Sustainability under the Science College, 3. Loyola Marymount University, which offers a concentration on Ecology and Sustainability) and two of them have graduate degrees in sustainability (1. National University, which offers an MS in Sustainability Management and 2. Rochester Institute of Technology, which offers several degrees including a dual Degree of MS/ME in Sustainable Engineering, an MS in Sustainable Systems and a PhD in Sustainability). More details of selected examples of sustainability classes incorporated into the SE curriculum can be found in Appendix 2.

A general conclusion from this analysis is that sustainability is not widely covered in systems engineering curriculum, which is in agreement with the literature review reported earlier. On the other hand, in many universities sustainability-related courses exist in other departments such as Civil and Environmental Engineering, which may be available to systems engineering students as electives. It also seems senior design projects present a good opportunity to expose the systems engineering students to sustainability-related design concepts. We would like to caution the reader here that the above research has limitations as it relies on the correctness of the information on the web. Also, our research did not include a detailed analysis of the syllabi for each course, which means that it is not unlikely that there are some systems courses that do include sustainability based on instructors' discretion. While a more in-depth research of syllabi would be able to reveal that information, this may be a very challenging undertaking as many professors do not prefer sharing their syllabi. This is a possible future research area beyond the scope of the current paper.

No.	Institution	BS	MS	PhD	Sustainability Related Courses/Programs
1	Air Force Institute of Technology, Dayton, OH, US		√	√	None
2	Boston University, Boston, MA, US		√	√	Course: ENG SE 543 - Sustainable Power Systems: Planning, Operation and Markets
3	Case Western Reserve University, Cleveland, OH, US	√			None
4*	Colorado School of Mines, Golden, CO, US		√	√	No SE degree
5	Colorado State University, Fort Collins, CO, US		√		None
6	Colorado Technical University, Colorado Springs, CO, US		√		Unknown (No curriculum details)
7	Cornell University, Ithaca, NY, US		√		Track: Sustainability Systems Engineering
8*	Embry-Riddle Aeronautical University, Daytona Beach, FL, US		√		No SE degree
9	Florida Institute of Technology, Melbourne, FL, US		√		Unknown (No curriculum details)
10	George Mason University, Fairfax, VA, US	√	√		None at SE Minor for Undergrads: Sustainability (Science) Grad Concentration: Energy and Sustainability (Science)
11	George Washington University, Washington, DC, US	√	√	√	None
12	Iowa State University, Ames, IA, US		√		None at SE Many electives
13	Johns Hopkins University, Baltimore, MD, US		√		None

14	Loyola Marymount University, Los Angeles, CA, US		√		Concentration: Ecology and Sustainability (no details on the E/S Courses)
15	Massachusetts Institute of Technology, Cambridge, MA, US		√		Course: Leadership Lab: Leading Sustainable Systems
16	Missouri University of Science and Technology, Rolla, MO, US		√	√	none (Elective under Civil: CE/EnvEng 360 Environmental Law and Regulations)
17	National University, LaJolla, CA, US		√		None in SE Master of Science in Sustainability Management
18	Naval Postgraduate School, Monterey, CA, US		√	√	None
19	Oakland University, Rochester, MI, US	√	√	√	None
20	Old Dominion University, Norfolk, VA, US		√		None
21	Penn State University at Great Valley, Malvern, PA, US		√		None
22	Portland State University, Portland, OR, US		√		None at SE Minors for Undergrads: in Sustainability, Sustainable Urban Development
23	Rochester Institute of Technology, Rochester, NY, US		√		Minor for Undergrads: Sustainable Product Development, Dual Degree: MS/ME in Sustainable Engineering (no details are available) MS in Sustainable Systems PhD in Sustainability
24	Southern Methodist University, Dallas, TX, US		√		None

					None
25	Southern Polytechnic State University, Marietta, GA, US		√		
26	Stevens Institute of Technology, Hoboken, NJ, US		√	√	None at SE Minor for Undergrads: Green Engineering.
27	Texas Tech University, Lubbock, TX, US		√		None
28	United State Military Academy, West Point, NY, US	√			Unknown (No curriculum details)
29	United States Naval Academy, Annapolis, MD, US	√			None
30	University of Alabama, Huntsville, Huntsville, AL, US		√	√	None
31	University of Arizona, Tucson, AZ, US	√	√	√	None at SE Many electives
32	University of Arkansas at Little Rock, Little Rock, AR, US	√	√		None
33	University of Maryland, College Park, MD, US		√	√	None in SE Minor for Undergrads: Environmental Economics and Policy
34*	University of Missouri - Rolla		√	√	Duplicate entry: Same as No. 16
35	University of North Carolina at Charlotte, Charlotte, UC, US	√			None
36	University of Pennsylvania, Philadelphia, PA, US	√	√	√	None at SE Minor for Undergrads: Energy and Sustainability
37	University of Southern California, Los Angeles, CA, US		√		Course: ISE 576 Industrial Ecology
38	University of Virginia, Charlottesville, VA, US	√	√	√	Course: SYS 6070 - Environmental Systems Analysis
39	University of Houston - Clear Lake, Houston, TX, US		√		None
40	United States Air Force Academy, Colorado Springs, CO, US	√			None

41	University of Maryland, Baltimore County (UMBC), Baltimore, MD, US		√		None
42	Washington University in St. Louis, St. Louis, MO, US	√			None at SE BS in Sustainability (Arts & Sciences)
43	University of St. Thomas, St. Paul, MN, US		√		None
44	University of Texas at Arlington, Arlington, TX, US		√		None at SE Many Electives
45	Texas A &M, College Station, TX		√		None at SE Many Electives
46	University of Texas at El Paso, El Paso, TX, US		√		None
47*	Walden University, Baltimore, MD, US		√		No SE degree

Table 1. Sustainability Related Courses/Programs in US-based Systems Engineering Programs (Source for the list of systems engineering academic programs: International Council on Systems Engineers-INCOSE[20]) Note: While the institutions marked with "*" are listed above for completeness based on the original list, they were not analyzed here since these institutions do not offer Systems Engineering degrees or they seem to be duplicate entries.

Major Sustainability Learning Objectives

Next, based on the aforementioned literature review, we have identified 19 major sustainability learning objectives applicable for systems engineering programs that have been included in different curricula in a related or similar way. These objectives and corresponding references where similar objectives were used are summarized in Table 2.

No	Learning Objectives	References
1	Apply systems engineering tools and techniques to solve sustainable design problems.	Borchers et al.[13]
2	Develop communication and collaboration skills to bring together different stakeholders for achieving environment, social and economic objectives of sustainability.	Crafton[4]
3	Demonstrate merits of corporate social and environmental responsibility for corporate success	Borchers et al.[13], Lynch-Caris and Sutherland[14], Walck[17]
4	Make Multi-objective Decisions and Risk Analysis considering the social, environmental and economic implications	Crafton[4]

5	Design sustainable products that consider recycling, reuse, and/or remanufacturing capabilities.	Borchers et al.[13], Bridges, Kumar [15], Lynch-Caris and Sutherland[14]
6	Understand alternative energy technologies for a successful system design	Kumar [15], Lynch-Caris and Sutherland[14]
7	Develop a clear understanding of legal and ethical issues underlying the environmental and social impact of goods and services	Borchers et al.[13]
8	Develop and maintain understanding of the meaning, goals, principles, history and issues of sustainable system design and development	Crafton[4]
9	Understand how sustainability can be applied in engineering and non-engineering systems	Kumar [15], Porter [10], Wheeler [6]
10	Understand the impact of systems engineer's actions to the bigger picture and to long terms implications related to environment, society and economy.	Kumar [15]
11	Demonstrate the importance of global thinking in systems engineering design, planning and execution.	Crafton[4]
12	Assess environmental impacts of systems design decisions via Life Cycle Analysis.	Borchers et al.[13], Lynch-Caris and Sutherland[14], Kumar [15]
13	Benchmark by being aware of locally and globally available sustainability success and failure stories	Wheeler [6]
14	Design system processes and practices that are not only lean but also sustainable	Lynch-Caris and Sutherland[14]
15	Make sourcing and supplier selection incorporating sustainability objectives	Borchers et al.[13], McDonald.[8]
16	Understand sustainability related metrics and their trade-offs	Borchers et al.[13]
17	Be familiar with software and technology that enables sustainable systems.	Tilbury et al.[18]
18	Understand how sustainable product marketing strategies can be developed	Bridges and Wilhelm[2]
19	Understand environmental standards (such as ISO 14001) and certifications for companies to attain sustainability	Bradfield[19]

Table 2. Major sustainability learning objectives based on the literature survey and references where similar or related objectives have been mentioned.

Matching Sustainability Learning Objectives to the Systems Engineering Curriculum

The Systems Engineering and Engineering Management Program at UNC Charlotte has started offering a B.S. in Systems Engineering in 2008. The program also grants a M.S. Degree in

Engineering Management. In the fall of 2009, the program added an Online MS in Engineering Management degree.

Current practice about sustainability education at UNC Charlotte Systems Engineering and Engineering Management program includes some courses that spend a few lectures of the course time on sustainability-related issues, depending on the instructor's discretion. Some instructors collaborate with local companies to expose students to projects related to sustainability as well. While these few efforts are definitely a good start, based on this study we suggest that more could be (and should be) done in the area of sustainability. For this purpose the sustainability learning objectives presented in Table 2, have been matched to the current Systems Engineering and Engineering Management course offerings as shown in Table 3. Table 3 can be considered as a preliminary roadmap for other Systems Engineering and Engineering Management programs to incorporate the different sustainability objectives into their different systems courses of the curriculum at the undergraduate level. (Corresponding descriptions of these systems engineering courses are provided in Appendix 1.)

While there seems to be two different ways to approach sustainability in the systems engineering curriculum, (introduce sustainability as one single course or intertwine sustainability into multiple courses in the entire curriculum), the authors of this paper believe that it would be a better alternative to have these learning objectives discussed above incorporated into the entire systems engineering curriculum. Sustainability is not a separate idea from systems engineering, it is a concept that could be and should be applied at every step of the systems engineering process, going hand in hand with the systems engineering concepts. On the other hand, development of a new course such as "Sustainable Systems Engineering" may be useful as well. This new course can go into more in-depth coverage of topics such as life-cycle assessment, energy audits, greenhouse gases and carbon footprint, environmental standards, and software/technology for sustainable system design. But we suggest this course in addition to implementing sustainability in the other courses, not instead of that.

One more thing we would like to highlight is that these courses have not yet been taught with the above-mentioned sustainability objectives included. Thus the level of success for these courses will likely depend on how much faculty commits to including sustainability in their courses, so perhaps faculty should be sold on these ideas as a first step of the implementation process.

No	Learning Objective	Possible BSSE course
1	Apply systems engineering tools and techniques to solve sustainable design problems.	• SEGR 2101 - Systems Engineering Concepts • SEGR 3101 – System Design and Deployment • SEGR 4131 – Product and Process Design • SEGR 4141 – Experimental Design
2	Develop communication and collaboration skills to bring together different stakeholders for achieving environment, social and economic	• SEGR 3111 - Project Management

	objectives of sustainability.	
3	Demonstrate merits of corporate social and environmental responsibility for corporate success	• SEGR 4131 – Product and Process Design
4	Make Multi-objective Decisions and Risk Analysis considering the social, environmental and economic implications	• SEGR 3101 – System Design and Deployment • SEGR 3102 - System Simulation, Modeling & Analysis • SEGR 3107 – Decision and Risk Analysis
5	Design sustainable products that consider recycling, reuse, and/or remanufacturing capabilities.	• SEGR 2101 - Systems Engineering Concepts • SEGR 3101 – System Design and Deployment • SEGR 4131 – Product and Process Design • SEGR 4141 – Experimental Design
6	Understand alternative energy technologies for a successful system design	• SEGR 3101 – System Design and Deployment • SEGR 4131 – Product and Process Design
7	Develop a clear understanding of legal and ethical issues underlying the environmental and social impact of goods and services	• SEGR 3111 - Project Management
8	Develop and maintain understanding of the meaning, goals, principles, history and issues of sustainable system design and development;	• SEGR 3101 – System Design and Deployment
9	Understand how sustainability can be applied in engineering and non-engineering systems	• SEGR 2101 - Systems Engineering Concepts • SEGR 3101 – System Design and Deployment
10	Understand the impact of systems engineer's actions to the bigger picture and to long term implications related to environment, society and economy.	• SEGR 2101 - Systems Engineering Concepts
11	Demonstrate the importance of global thinking in systems engineering design, planning and execution.	• SEGR 3122 Implementation of Logistics Systems and Supply Chains
12	Assess environmental impacts of systems design decisions via Life Cycle Analysis	• SEGR 3101 – System Design and Deployment • SEGR 4131 – Product and Process Design
13	Benchmark by being aware of locally and globally available sustainability success and failure stories	• SEGR 4131 – Product and Process Design • SEGR 3111 - Project Management

14	Design system processes and practices that are not only lean but also sustainable	• SEGR 3101 – System Design and Deployment
15	Make sourcing and supplier selection incorporating sustainability objectives	• SEGR 3122 Implementation of Logistics Systems and Supply Chains
16	Understand sustainability related metrics and their trade-offs	• SEGR 3112 Value Engineering Management
17	Be familiar with software and technology that enables sustainable systems.	• SEGR 3101 – System Design and Deployment • SEGR 4131 – Product and Process Design
18	Understand how sustainable product marketing strategies can be developed	• SEGR 4131 – Product and Process Design
19	Understand environmental standards (such as ISO 14001) and certifications for companies to attain sustainability	• ENGR 3670 Total Quality Systems

Table 3. Learning Objectives for Sustainability Education with Possible Matching Courses

Summary and Conclusions

In this study, we proposed a preliminary road-map for Systems Engineering programs for curriculum design to incorporate sustainability into their curriculum. Our methodology incorporated a literature review to investigate the previously developed courses that have already successfully incorporated sustainability into their curriculum. We have identified 19 major objectives for the systems engineering curriculum and matched these objectives with specific undergraduate level courses at UNC Charlotte's Systems Engineering degree program.

Benchmarking of major accredited systems engineering programs showed that sustainability is still a new field for the systems engineering discipline, but very good examples exist. While it is a challenging task, future research may include a more in-depth analysis of syllabi from different institutions or conducting related surveys among the systems engineering faculty. This will give us a better picture on the current coverage of sustainability in systems engineering programs. A fine tuning of the proposed objectives might be necessary after going through an implementation of the proposed roadmap. Also, exploring how these objectives possibly align with ABET goals and objectives might be worth looking into in the future.

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Appendix 1

BSSE Course	Description
SEGR 2101 - Systems Engineering Concepts	This course provides the foundation for systems engineering processes and practices. The contents cover the discussion of current systems issues, basic systems engineering processes, and the roles of systems engineering professionals in a global business environment.
SEGR 3101 – System Design and Deployment	Focuses on the basics of systems design, analysis, and implementation. It covers system design elements, system interface issues, system decomposition, and system integration. The emphasis is on the effective design and integration of system operations and successful deployment of systems design results.
SEGR 3102 - System Simulation, Modeling & Analysis	Focuses on the study of discrete-event simulation and its use in the analysis and design of systems. The emphasis is on using simulation software for simulation modeling and analysis with practical applications to design, analysis, and improvement of diverse systems.
SEGR 3107 Decision and Risk Analysis	This course aims to provide some useful tools for analyzing difficult decisions and making the right choice. After introducing components and challenges of decision making, the course will proceed with the discussion of structuring decisions using decision trees and influence diagrams. Decisions under conflicting objectives and multiple criteria will be covered as well as sensitivity and risk analysis.
SEGR 3111 - Project Management	Focuses on the study of various aspects of project management techniques and issues, and the use of conceptual, analytical, and systems approaches in managing engineering projects and activities. It includes the development and writing of project plans and reports for engineering and business operations.
SEGR 3112 Value Engineering Management	Analyzes the requirements of a project to achieve the highest performance for essential functions at the lowest costs over the life of the project. The "best value" is achieved by a multidisciplinary team effort through the study of alternative design concepts, materials, and methods.
SEGR 3122 - Implementation of Logistics Systems and Supply Chains	This course reviews and analyzes real-life logistics and supply chain implementation cases. Different industry supply chains are compared and benchmarking is emphasized through review of industry best practices.
ENGR 3670 - Total Quality Systems	An interdisciplinary approach to principles and practice in the applications of continuous quality improvement (CQI) and Total Quality Management (TQM). Classroom work on major applications, re-engineering processes; process mapping, personal effectiveness and time management; technical presentations; CQI tools, statistical process control, designed experimentation; management and planning tools, engineering economy, and case studies; assignments and projects in team building, communication, and group problem solving.
SEGR 4131 – Product and	Focuses on how to achieve a high-quality, customer-oriented product development process, from technology and product innovation, to design

Process Design	and development, leading up to production. Design for Six Sigma (DFSS) is the main technology discussed plus other product design approaches, such as design for cost, design for safety, and design for environment.
SEGR 4141 - Engineering Experimental Design	Focuses on how to achieve high-quality/low-cost systems based on Taguchi methods, design of experiments methods, and statistical analysis of data. Also includes introduction to response surface methods.

Appendix 2

Examples of sustainability well incorporated into the undergraduate curriculum include

1. **George Mason University: a minor in sustainability.**
   Requires 16 credits where 8 credits are core courses (NCLC 210: Sustainable World, EVPP 480: Sustainability in Action) and 8 are electives that may be selected from different fields such as Anthropology, Climate Dynamics, Communications, Economics, Ecotourism, Engineering, Environmental Science, Geography, Geology, History, Parks, Recreation, and Leisure Studies, Philosophy and Sociology.[21]
2. **University of Pennsylvania: BS in Systems Science and Engineering.**
   It offers a minor in Energy and Sustainability with the following list of elective courses: MEAM 250 Energy Systems, Resources and Technology, EAS 301 Climate Policy and Technology, EAS 401 Energy and its Impacts, EAS 402 Renewable Energy and its Impacts, EAS 403 Energy Systems and Policy, CBE 375 Engineering and the Environment, CBE 545 Electrochemical Energy Conversion and Storage, MEAM 402 Energy Engineering, ESE 560 Sustainable Development of Water Resource Systems, ESE 521 The Physics of Solid State Energy Devices. [22]

Examples of sustainability well incorporated into the graduate curriculum include:

1. **Cornell University: a track on Sustainability Systems Engineering.**
   It requires completion of 17 credits including courses such as NTRES 6340 International Conservation: Communities and the Management of the World's Natural Resources, AEM 6510 Environmental and Resource Economics, CEE 6650 Transportation, Environment, and Energy Systems and AEM 6600 Agroecosystems, Economic Development, and the Environment. [23]
2. **George Mason University, an MS in Energy and Sustainability.**
   According to their website description, "The master's degree program in interdisciplinary studies (MAIS) is designed for students who seek a degree that integrates knowledge from several disciplines. It addresses a rapidly evolving demand for specialized and individualized graduate study. This concentration is particularly relevant for students who are pursuing or interested in pursuing careers in energy and environmentally related applications in the law, national and international policy, government, print and media journalism, public and social service, teaching, advanced graduate studies, ethics, business, and basic and applied research. A good source of useful information on careers and internships in the renewable energy field can be found on the internet." [24]

Examples for Sustainability Related Courses in Systems Engineering Programs:

1. **Boston University, ENG SE 543 - Sustainable Power Systems: Planning, Operation and Markets:**
   According to their website description, "Breakthroughs in clean energy generation technologies and the advantage of exploiting efficiently the available work in fossil fuels will render electricity the dominant energy form in a sustainable environment future. We review the key characteristics of Electric Power Transmission and Distribution (T&D) networks and the associated planning and operation requirements that ensure supply adequacy, system security and stability. Capital asset investment and operation cost minimization is discussed in a systems engineering context where the assets as well as the dynamic behavior of generators, T&D networks, and loads interact. Recent developments in the formation of competitive wholesale markets at the High Voltage Transmission system level, the associated market participation and clearing rules and the market clearing optimization algorithms are presented and analyzed in terms of their effectiveness in fostering cost reflective price signals and competitive conditions that encourage optimal distributed/not-centralized investment and operating decisions. Finally, we present T&D congestion and supply-demand imbalance related barriers to the widespread adoption of environmentally friendly and economically efficient technological breakthroughs, and propose a systems engineering and real-time retail-market based coordination of centralized as well as decentralized generation, storage and load management resources that is able to achieve desirable synergies and mitigate these barriers." [25]
2. **MIT, Leadership Lab: Leading Sustainable Systems:**
   According to their website description, "This course addresses key sustainability challenges faced by business and society, exploring alternative ways to view organizations that draw attention to cross-boundary interdependencies and help leaders at all levels develop their capacity to collaborate for systemic change. Students develop the skills to help people surface and reflect on mental models and practices that keep organizations stuck in unproductive system dynamics." [26]
3. **University of Southern California, ISE 576 Industrial Ecology:**
   According to their description, "Concepts and methods to analyze the environmental impacts of industrial systems, including life-cycle assessment, material flow analysis, design for environment and sustainable consumption." [27]

4. **University of Virginia, BS in Systems Engineering, SYS 6070 - Environmental Systems Analysis:**
   According to their description, it "focuses on the infrastructure for the provision of drinking water, wastewater/sewage, and solid waste management services in the context of the environmental systems in which they are embedded and the institutional framework within which they must operate. It begins with coverage of the infrastructure design, operation, and maintenance, proceeds to a treatment of the concept of integrated sanitation systems, and then considers the major environmental issues relevant to these services, including global warming, the millennium development goals, and sustainability. It also includes a study of the common tools in environmental systems analysis: lifecycle assessment, environmental economics, mass and energy balances, benefit-cost analysis, risk analysis, and environmental forecasting." [28]