Incorporating systems-based life cycle thinking and sustainability in engineering curricula

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ABSTRACT
Systems-based life cycle thinking and sustainability have become significantly important in higher education across various disciplines, with engineering being no exception. Engineering educators need to address this evolution because the domestic and global marketplace are changing dramatically in a way that continues to address the downward spiral of our Earth's environmental conditions. Our increasing population fuels an increasing appetite for energy, materials and resources, and this has placed added pressure on our planet. Today's engineers are increasingly asked to make economically and environmentally informed decisions based on the materials, processes, construction and policies being implemented in their innovations. Although engineers are highly trained in analysis, most of them receive effectively minimal training in evaluating the life cycle energy and environmental impacts of materials, products, systems and services, especially mainstream disciplines such as mechanical and electrical engineering. These impacts can include numerous variables, such as carbon dioxide, particulate matter, volatile organic compounds, sulfur oxides, nitrogen oxides and others, all of which contribute to global warming, acidification, eutrophication, human health impacts and many more. This work will introduce the importance of incorporating systems-based life cycle thinking and sustainability concepts in engineering curricula by primarily focusing on two courses that are currently being implemented at the University of Michigan-Flint. Academic disciplines such as industrial ecology and life cycle assessment, which are part this incorporation, are essential in helping engineers understand the importance of using scientific assessment to evaluate systematic sustainability impacts. The overall goal of this work is to share more details of this process and broaden the thinking of sustainability for engineering education.

INTRODUCTION
One of the most common definitions of sustainability resulted from the work of the Brundtland Commission of the United Nations, which stated that "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Sustainability has become significantly important in higher education across various disciplines. Engineering educators need to address this evolution because the domestic and global marketplace are changing dramatically in a way that continues to address the downward spiral of our Earth's environmental conditions. Our increasing population fuels an

increasing appetite for energy, materials and resources, and this has placed added pressure on our planet.

Today's engineers are increasingly asked to make economically and environmentally informed decisions based on the materials, processes, construction and policies being implemented in their innovations. This often requires knowledge in analyzing energy and environmental impacts of various products and systems, followed by making whole systems-based and life-cycle thinking techniques to improve their overall use of energy, materials and natural resources. Although engineers are highly trained in analysis, most of them receive effectively minimal training in evaluating the life cycle energy and environmental impacts of materials, products, systems and services, especially in mainstream disciplines such as mechanical and electrical engineering. These impacts can include numerous variables, such as carbon dioxide, particulate matter, volatile organic compounds, sulfur oxides, nitrogen oxides and others, all of which contribute to global warming, acidification, eutrophication, human health impacts and many more.

This work will introduce the importance of incorporating systems-based life cycle thinking and sustainability concepts in engineering curricula by primarily focusing on two courses that are currently being implemented at the University of Michigan-Flint (UM-Flint). The UM-Flint's Department of Computer Science, Engineering and Physics offers B.S. degrees *in Mechanical Engineering* and *General Engineering*, with a B.S. in *Industrial and Operations Engineering* being implemented in the next academic year. The General Engineering program provides students the option to select one of the following tracks: *Computer Engineering, Engineering Management, Engineering Physics* and *Environmental Engineering*. The courses being introduced will serve as electives in all engineering programs and also as part of the *Environmental Engineering* track. Academic disciplines such as industrial ecology, life cycle assessment (LCA) and sustainable design, which are part of this incorporation, are essential in helping engineers of all disciplines understand the importance of using scientific assessment to evaluate systematic sustainability impacts. The overall goal of this work is to share more details of this process and broaden the thinking of sustainability for engineering education.

IMPLEMENTATION

Technology and the engineering behind it strongly affect every facet of society. The same can be said for the relationship between technology and the natural world. It is this interdependence that stresses the need for sustainable engineering, industrial ecology and LCA. While modern technology has brought about enormous benefits to society, it has also introduced increasing concerns about its impacts on the natural environment.

The approach in incorporating systems-based life cycle thinking and sustainability in engineering curricula is to introduce students to the concept of industrial ecology, LCA and sustainable engineering of products and systems. The term "products and systems" denotes any physical entity that can be imagined. This could mean something as simple as a paper cup or something complex such as an electricity grid. Every product and system can have lower environmental impacts and achieve a higher state of sustainability by using less energy and materials, but this is not always straightforward.

The first course that will be added to the curriculum will focus on LCA. LCA is a method used to quantify and measure the environmental impacts of a material, product, system or service (Figure 1). More specifically, LCA is a systems-based process of assessing and calculating the human health, energy and environmental burdens of those commodities from "cradle to grave." This is done by compiling and evaluating the input water, energy and materials, output by-products, pollutants, emissions and waste, and the potential environmental impacts, resource use and waste generation throughout the life cycle (Figure 2). The life cycle of a material, product, system or service extends from cradle-to-grave: from materials acquisition and production, through manufacturing, system use and maintenance, and finally through the end of the system's life. Environmental impacts include categories such as global warming potential, acidification, eutrophication, photochemical smog, ozone depletion, and many more.

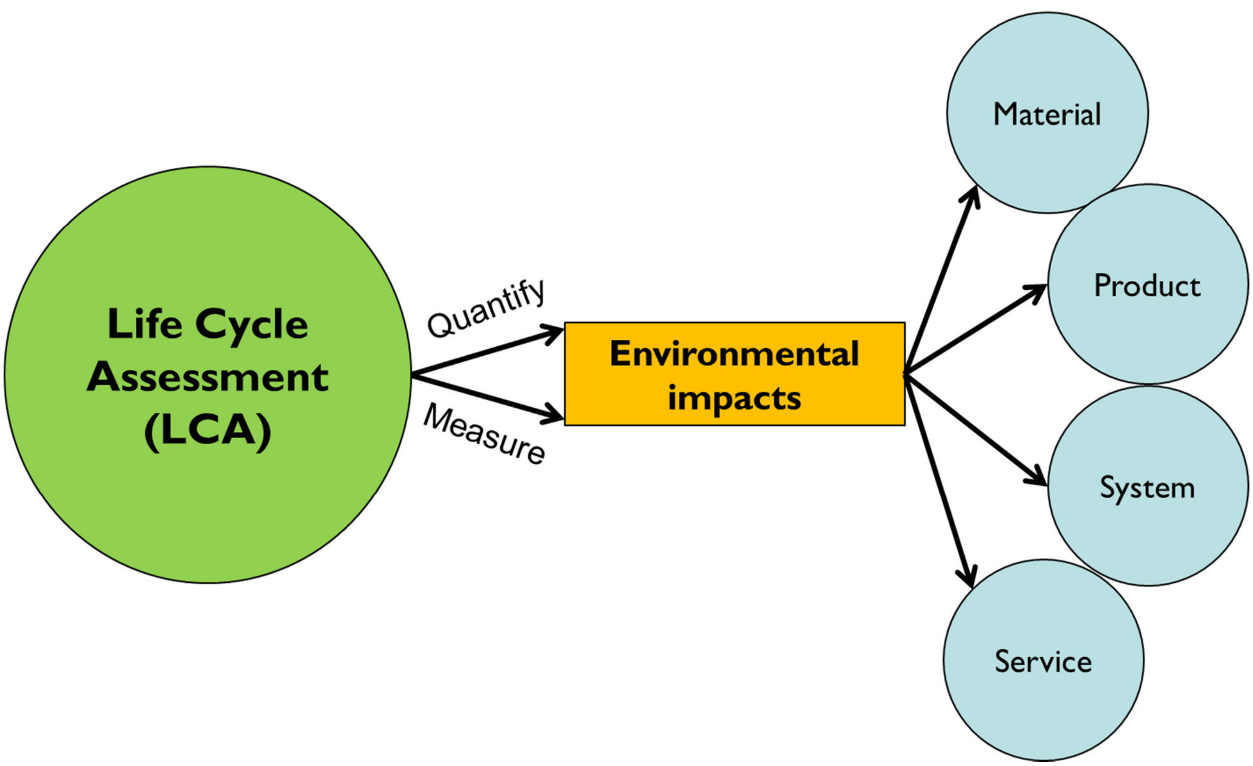

Figure 1 What is Life Cycle Assessment?

LCA provides a method to 1) collect and manage materials and energy information for a life cycle and 2) assess the potential energy and environmental impacts of materials and energy flows. LCA has become an extremely useful and popular option in the business world to assess alternative strategies [2]. Traditionally, the use phase of a product or system has been given the most consideration. However, the true impact of a technology cannot be accurately determined without considering other phases of the life cycle. For example, a common misconception about renewable energy sources is that they have far less environmental impacts compared to conventional sources. Recent studies have shown that this is not always the case [3–7]. Thus, LCA is a good way to avoid unintended consequences and provides a useful tool to assess potential strategies in implementing emerging technologies sustainability.

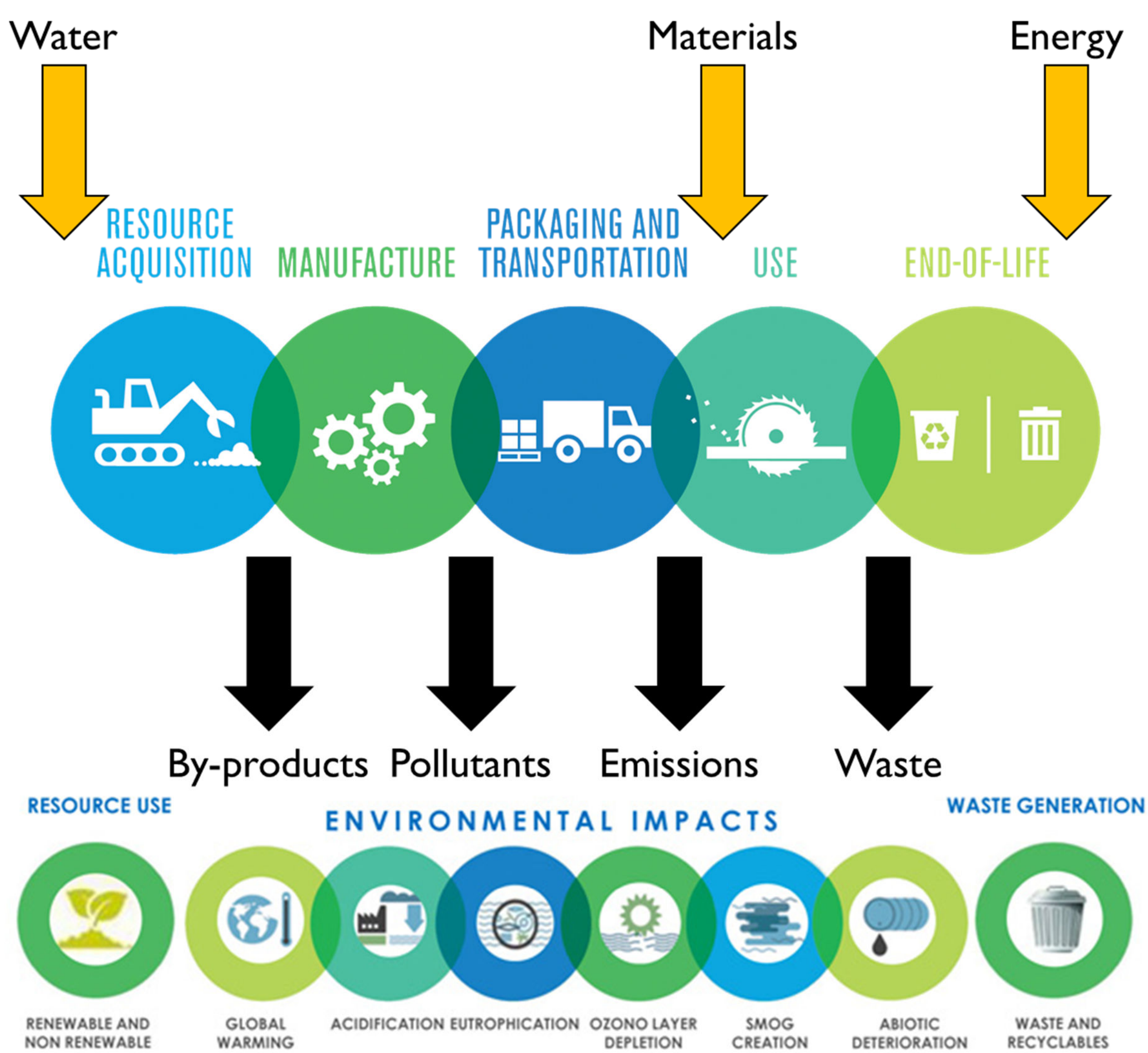

Figure 2 Inputs and Outputs of a Life Cycle Assessment

LCA is a standard governed by the International Organization for Standardization (ISO) and it outlines the specific protocols as to how it should be performed in terms of data collection, analysis and implementation [8]. It is being used by governments and non-profit organizations such as the U.S. Environmental Protection Agency (EPA) and U.S. Green Building Council (GBC) to make policy decisions and implement standards. The U.S. EPA incorporated LCA to make established policies regarding the National Renewable Fuel Standard (RFS) program, which determine the future production of renewable fuel categories. LCA was used to determine whether renewable fuels produced under varying conditions meet the GHG thresholds for the different categories of renewable fuels [9]. The U.S. GBC is a non-profit organization that is best known for the Leadership in Energy and Environmental Design (LEED) green building rating system. LEED version 4 includes credits that incorporates life cycle thinking, whereby the entire life cycle of a product is examined. This means the production process and the materials used are identified, and the impacts of those processes and materials are assessed, both upstream (from point of manufacturing or use toward raw materials extractions) and downstream (from that point towards the end-of-life).

The second course focuses on the application of the systems-based life-cycle principles by introducing students to the sustainable design of products and systems, also known as *Design for Environment*. While LCA can teach students the concepts and methodology in executing LCAs of engineered products and systems, *Design for Environment* focuses on analyzing and designing technologies that are clean and sustainable throughout their life cycles. The fundamental concepts that will be introduced in this class will be:

- Whole systems and life-cycle thinking: In order to fully assess and act upon the energy and environmental impacts of products and systems, whole systems and life-cycle thinking are extremely important. Whole systems thinking allows one to see the big-picture impacts of the system that a product is part of, while life-cycle thinking forces us to assess impacts from cradle to grave.
- Energy-efficient design: Energy is critical to society's basic needs. This concept looks at ways in which we can rethink ways in which our products and systems use energy by incorporating more renewable energy use and design for energy efficiency. For example, using locally-produced materials reduces transportation costs and produces less greenhouse gas emissions.
- Design for product lifetime: One common phase of a product or system that consumers do not generally think about is end-of-life, or the disposal phase. By applying ideas such as design for disassembly, design for repair, design for upgrade, design for recycling and design for remanufacturing, one can already improve the sustainability profile of products and systems by redirecting the waste flow and striving to create a "closed system," where there is an infinite recycling of resources.

- Green materials selection: The proper selection of green materials in designing and manufacturing products and systems is another key component. Green materials are abundant, non-toxic, use minimal resources in production, meets or exceed regulations, have good end-of-life options and are affordable. Selecting the right materials involves incorporating these different criteria in design.
- Lightweighting: Replacing conventional materials with lighter ones can often lead to sustainable improvements. This is evident in automobiles and planes, since lighter versions use less fuel for example. However, the costs and benefits of substituting materials needs to consider long-term cost, strength and performance.

ACTIVE LEARNING

An important objective of this implementation will be accomplished through the application of the above-mentioned concepts by incorporating "learning by doing" activities. One such activity involves redesigning a computer processing unit (CPU). In this lab, students, in groups, will disassemble an obsolete CPU and critique the disassembly process by studying the type and weight of materials, the ease of disassembly, etc. The goal is to apply the above mentioned concepts in redesigning a more sustainable version of the given product. For example, students will consider whether the CPU can be designed for increased recyclability or easier disassembly and suggest changes accordingly. Another activity that is planned is for students to design and develop a sustainability rating system for a product or system of their choice. Building and computer products already have well-established green rating systems. Students will use the above-mentioned concepts and these existing rating systems to either improve upon and create new rating systems that allow for determining the sustainability of various products and systems. Finally, the instructor also include field trips to notable green buildings and electronic waste recycling facilities for students to get a first-hand experience as to how products and systems can be design and disposed of in a sustainable fashion. Students do not effectively learn and remember concepts by just listening and watching lectures. Rather, they "learn by doing," and an emphasis on active learning will be made in this course, in the context of sustainable design.

TEACHING INNOVATION

Teaching students how to apply specific sustainability concepts through active learning strategies is not a practice that has been implemented on a wide scale. These concepts provide the know-how that is critical in both understanding and applying sustainability throughout the overall system that we participate in and over the entire life cycle of products and systems. The combination of active learning strategies and the teaching of fundamental concepts in sustainable design will allow students to develop skills that will be useful in the job market. To further implement some of the fundamental concepts, students may also be involved in software applications where they can actually design alternative versions of products that are more sustainable.

IMPACT OF LEARNING

The overall goal of this implementation is to address a critical gap between the students' skillset and their career goals. The instructor performed an informal survey of students at the UM-Flint and many agreed that those who wish to be sustainability consultants, green designers and sustainability engineers within companies, both large and small, sometimes lack the necessary skills to become one. For example, engineers often need to assess complex energy and environmental data and then develop solutions, which are often not straightforward, for various products and systems. When students make the connection between the importance of learning and their career goals, they will be more motivated. Students will enjoy their learning experience by learning the fundamental concepts of sustainable engineering and life cycle thinking, exploring ways in which they are applied in real life, and then applying those concepts through active learning activities. This learning sequence will also help them retain the skills and knowledge they gather from that experience.

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Biographical Information

Seung-Jin Lee is an Assistant Professor of Sustainability and Mechanical Engineering in the Department of Earth and Resource Science and Department of Computer Science, Engineering and Physics at the University of Michigan-Flint. He was formerly an Oak Ridge Institute of Science and Education (ORISE) Postdoctoral Research Fellow at the U.S. Environmental Protection Agency (EPA), National Risk Management Research Lab (NRMRL), Sustainable Technology Division (STD), in Cincinnati, Ohio. His research focus is on the life cycle sustainability of emerging technologies, such as biofuels, green buildings, and consumer products. His tools of research include life cycle assessment (LCA), industrial ecology, material flow analysis, energy efficiency, market diffusion models, reuse and recycling, and sustainable development. He received his Ph.D. in Mechanical Engineering from the University of Washington.