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How to Address Sustainability in a Mechanical Engineering Program — Implementation and Challenges

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Abstract

With the growing consciousness of depleting material and energy resources, the concepts of renewability and sustainability are becoming increasingly important. Sustainable engineering requires improved design of products, systems, and services, targeting better environmental and social performance together with economic viability. The challenge is to reduce this powerful abstract concept into a rigorous educational framework, with clear-cut methods, tools, and metrics, so it can be integrated into engineering curricula and practiced by professionals. The United Nations defines sustainability in terms of development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This requires a mutually optimal usage of natural, societal, and economic resources. Sustainability education necessitates the use of unconventional approaches as against the traditional lecture-based style. Some institutions have tried to develop a sustainability curriculum using the learning pedagogies of problem-based and project-based learning (PPBL). Using PPBL as a teaching and learning strategy facilitates cooperative learning, critical thinking, systemic reasoning, creative approach, and societal awareness, which are the core values of sustainability. However, translating this into a working curriculum is quite complex, and raises implementation issues such as physical arrangements for an active learning environment, changes in the assessment and grading system, providing both teachers and students with at least rudimentary knowledge of PPBL methods, achieving institutional support, etc. Another issue is the program-level decision of having a full dedicated course on sustainable engineering, or introducing modules on environmental engineering, green engineering, pollution prevention, waste minimization, and design for environment within a few relevant courses. The first part of this paper introduces the issues of sustainable development and sustainable engineering; the overlap of the terms sustainable, renewable, and recyclable; education for sustainable development; and pedagogy for sustainability education. The second part describes the ongoing implementation of sustainability content in the Mechanical Engineering program at our university, giving a roadmap for sustainability curriculum, and giving examples from the Product Design and the Engineering Materials courses. The last part of the paper discusses the major challenges in sustainability education, such as sustainability practice in academia, policy making issues, content overload, cultural issues, and the gray boundary between environmental protection and sustainability.

Keywords: Sustainable development; sustainable engineering; sustainability education; problem-based and project-based learning; sustainable, renewable, recyclable; challenges

Introduction

The concept of sustainability has emerged from the realization that the world has finite resources, and there is a delicate ecosystem in which these resources can be utilized for development. Sustainability addresses the capability of humans to coexist with nature in a manner that allows long term prosperity and growth for both. Sustainability is comprised of three core dimensions: environmental, economic, and social [1]. To practice sustainability is to provide technological, economic, and social growth without compromising the environment, the society, and the livelihood of people. An important factor in the concept of sustainability is also the consideration that growth is not just for the current population; it should not adversely affect future generations [2].

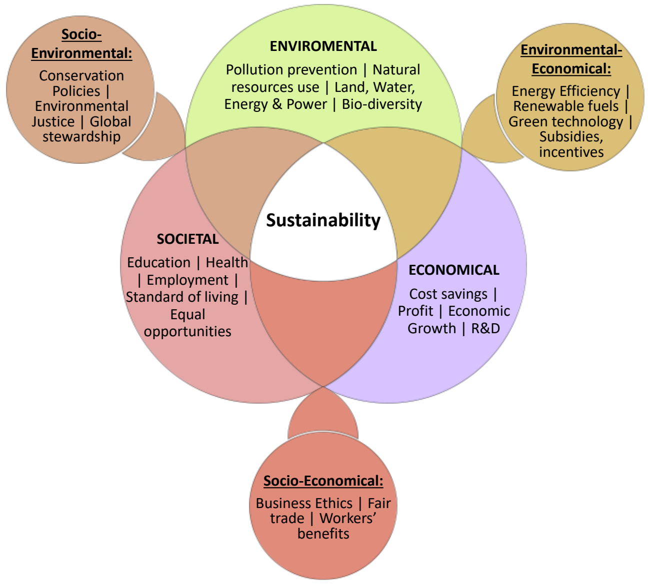

Figure-1 The three major attributes of sustainability, and their interactions

Figure-1 shows the three major aspects of sustainable development (environmental, economic, and social), their most important constituents, and the interactions among them [3]. Environmental factors include the use of natural resources, pollution prevention, biodiversity, and ecological health. Standards of living, provisions for education and jobs, and equal opportunities for all sectors of society comprise the social aspects. Economic considerations are drivers for growth, profit, cost reduction, and investments in research and development. One interaction leads to socio-economic concerns such as business ethics, fair trade, and workers' benefits. The intersection of economic and environmental spheres generates issues like higher energy efficiency, development of renewable fuels and green technologies, etc. At the social-environmental juncture are aspects like policies for conservation and environmental protection, system for environmental justice, and worldwide consensus and for the sustainable use of natural resources [4].

Sustainable Development

If sustainability is the long-term goal, sustainable development is the pathway that leads to it. The seminal report "Our Common Future" published by the United Nations in 1987 [5] famously described sustainability as "meets the needs of the present without compromising the ability of future generations to meet their own needs". Keeping in mind the environmental, economic, and social aspects, the development should not compromise present growth, while minimizing social and economic risk and cost to the current and future inhabitants of the ecology. The ecology can be divided into three levels: local, regional, and global; and the impact at each level needs to be considered [6].

Current Work

Over the last couple of years, the College of Engineering at our university has gone through a rigorous curriculum review and modernization effort. As part of this activity, some faculty members of the Mechanical Engineering (ME) program are attempting to introduce sustainability as a visible thread in certain courses. Some of the ideas presented below are suggestions for future incorporation in the curricula, while some are already being introduced during the ongoing semester. In line with the core principles of sustainable engineering, revisions and adaptations are planned/undertaken in course outcomes and objectives, course delivery and instructional strategy, and assessment schemes. Presented below are some significant observations related to the incorporation of sustainability principles in engineering education, from our own experiences in different ME courses, and from published papers on this issue.

Sustainable Development and Sustainable Engineering

Sustainable Engineering (SE) is the science of applying the principles of engineering and design in a manner that fosters positive social and economic development while minimizing environmental impact. Design for sustainability, also called (environmentally) sustainable design, or eco-design is the way of designing products, processes and systems that enable sustainable development [2].

Sustainable engineering is the key for sustainable development. It requires a holistic approach to the engineering problem, considering the entire lifecycle of the engineering solution and its implications on the users and the environment. An integrated approach is required to eliminate the possibility of any negative emergent factors that could affect sustainability. This makes every engineering problem a multi-variable optimization problem where the ultimate goal is to maximize productivity within the constraints of healthy environment, happy society, and thriving economy. Many authors have proposed various principles to define the scope of sustainable engineering, outlining topics such as energy conservation, social equity, waste reduction, and environmental restoration, to name a few.

The Coalition for Environmentally Responsible Economies (CERES) in 1989 proposed the first code for companies to practice sustainable engineering, including ideas such as information management and reporting and managerial commitment along with the engineering concepts such as waste reduction and disposal [7]. Further work by the United Nations [8], Haughton [9], Earth Commission Charter [10] and various governments [11, 12] shed more light on principles such as socio-economic equity, promoting good governance, alleviating poverty, and capacity building which broadened the scope for economic and social sustainability. Becker [13] defined the now well-known characteristics of sustainable systems as resilience, self-sufficiency, and collaboration. Valentin and Spangenberg [14] and McDonough and Braungart [15] built on these principles and represented them in a prismatic manner. Gagnon et al [1] summarized many of the above principles by representing them in a multidimensional triangular chart, tying the environmental, social and economic principles together. Lozano [16] also describes a three-dimensional approach to sustainability based on similar principles. Glavic [2] provides an update on these sustainability principles for the modern-day engineer.

Sustainability principles, and sustainable design and engineering directly affect technologies, processes, and products, which in turn drive the human lifestyle [3]. The hierarchical arrangement of these factors is shown in Figure-2. Sustainability principles are drivers for sustainable design, a thought process. Sustainable engineering is the technical implementation of these design ideas. This transformation (abstract idea to concrete product) is often a complex process, requiring intermittent design changes and adaptations. Then comes the implementation or development of relevant technologies that generate the processes and the products. Principles of sustainable design and engineering pass through this portal, affecting people's lifestyle and creating changes in society, sometimes leading to new global trends [2].

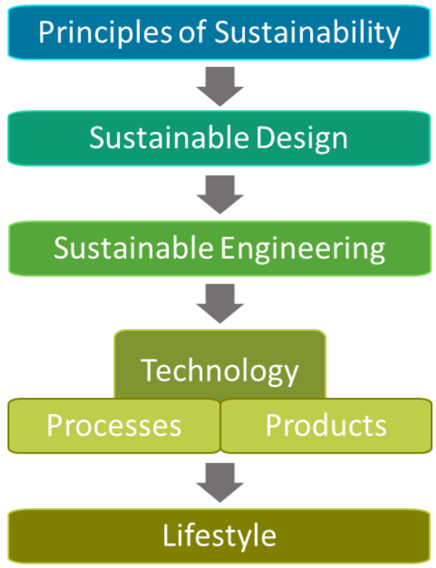

Figure-2 How sustainability and technology affect human lifestyles

Sustainable, Renewable, Recyclable?

With the continuing problems of deforestation, greenhouse emissions, ozone layer depletion, global warming, and overall environmental degradation, it looks like the world is running on a self-destruct mode. In the words of Terry Swearingen, 1997 winner of the Goldman Environmental Prize "we are living on this planet as if we had another one to go to." Sustainability is one of the top most priorities today. Recyclable and renewable resources (materials and energies) can help in making the planet better, safer, and greener, for current and future generations. To recycle means to transform waste products into new supplies or products. Resources that are renewable can be naturally and organically replenished over a given time period [17]. For a good "today" and for a better "tomorrow," it is important to understand and spread awareness about recyclable and renewable materials and energies that work in a sustainable manner.

A native American proverb tells us that "we do not inherit the earth from our ancestors; we borrow it from our children." There are both positive and negative aspects to renewable and recyclable materials. Knowing how these two types of materials work is critical in trying to make our planet more sustainable. Let us take logging of timber for the worldwide construction industry as an example. Which is a better option for sustainable living? Should we opt for renewables and risk deforestation, or should we go for recyclables and face the hazard of increased pollution if the target of recycling is not met? An optimal solution is quite complex. Another option is 'recyclable renewables,' with the possibility of recycling our renewable products. Materials such as renewable plastics (made from cellulosic materials instead of petrochemicals) would be an excellent alternative, and may be a backbone of sustainability in the future [17].

Some questions in this regard can be quite and thought-provoking. What is the difference between recyclable and recycled? How is a circular economy different from a linear economy? Do the terms sustainable and renewable mean the same thing? What is the difference between renewable and sustainable resources? Answers to these intriguing questions are left to the reader to be explored, but form the basis for a clear-cut understanding of sustainable development and engineering, and a safeguard against many widespread misconceptions [18].

Education for Sustainable Development

The world needs technical solutions, and engineering methods and practices that have less negative impact on the environment, making the ecosystem more resilient and sustainable. New approaches are needed that require, among others, a new type of engineering approach in the design and control of systems, and the development of processes and products. These should focus on the use of environment friendly materials, and production systems with improved efficiency of energy, materials, and other resources. Engineering has a crucial role in shaping the development of societies. Engineering education is therefore critical for sustainability. According to UNESCO, there is an urgent need to align engineering education with sustainable development [19, 20].

In 2015, the United Nations (UN) introduced the 2030 Agenda for Sustainable Development that outlined 17 Sustainable Development Goals (SDGs). This included the identification of 169 targets and 230 indicators to monitor and measure progress towards the successful implementation of these SDGs [21]. Education for sustainable development (ESD) is one of the specific targets of SDG 4 (quality education), which is recognized as a critical enabler for sustainable development. ESD is not only important in SDG 4, but is also essential for the fulfillment of all other SDGs.

Pedagogy for Sustainability Education

Engineering education has the responsibility to educate engineers to think holistically to be able to remediate the existing sustainable problems and prevent future ones. Though some engineering universities have achieved a few milestones regarding ESD, full integration of sustainability in engineering education is not an easy task. Due to the interdisciplinary nature of engineering systems, processes, and designs, teaching sustainable development in the context of engineering education necessitates the use of unconventional approaches as opposed to the traditional lecture-based style [22]. These include problem-based learning (PBL) and project-based learning (PrBL), together known as PPBL; case studies; collaborative group-based learning; and the conceive, design, implement, operate (CDIO) approach. Experience of various institutions discussed and summarized by [23] indicated that sustainable development is not a new set of tools or an addition to the existing skills set; rather it represents a new integrative principle. Therefore, a course dedicated to sustainable development is not sufficient. Sustainability needs to be embedded within many courses through an integrated approach, employing the pedagogical techniques of cooperative learning, critical thinking, and systemic reasoning. The target is the practice and implementation of a creative approach and societal awareness. The examples of sustainability modules in our university, given in a later section, demonstrate the use of some of these active learning and group-based approaches.

Sustainability in Mechanical Engineering Program

The Mechanical Engineering program at our university is divided into four focus groups: Materials and manufacturing (MM), Applied mechanics and design (AMD), Dynamics and control (DC), and Thermofluids engineering (TFE). Students are also required to take some General engineering (GE) and University elective (UE) courses. Courses in the MM stream are Workshop Practice, Materials Science, Engineering Materials, and Manufacturing Processes. Courses in the MM stream are Product Design, Machine Design I, Capstone Design, and Final Year Project. Examples of sustainable engineering concepts and exercises given below are from one course each from the MM and AMD streams.

Roadmap for Sustainability Curriculum

Changes in curriculum content and delivery are always a challenge, and face resistance from all stake holders (faculty, students, and management). Overall recommendation from the authors, for a meaningful inclusion of sustainability concepts in the ME program, is to make the changes minimal but effective. The approach should be two-pronged: inclusion of sustainability modules in relevant courses; and introduction of a full course on sustainable engineering as a final-year elective, without disturbing the curricular structure (core ME courses).

Basic concepts of sustainability should be introduced in the very first year, in the GE course Introduction to Engineering. Short modules of sustainable engineering should be incorporated in the MM courses Materials Science (MS), Engineering Materials (EM), and Manufacturing processes (MP); the AMD courses Product Design (PD), Machine Design I, and Capstone Design; the TFE course Design of Thermal Systems; and the Final Year Project. As mentioned above, a stand-alone elective-level course on Sustainable Engineering should be added in the final-year of the program. It should be pointed out that after incorporation of the ongoing course modernization, the MS course will be changed to Materials Science and Engineering (MSE), and the EM course to Modern Materials and Manufacturing (MMM).

Product Design Course

Product Design (PD) is a project based course that covers the product design method or process. Major topics covered are product design strategies; identification of customer needs; translation of customer needs into product design specifications; concept generation, selection and testing; product architecture with focus on developing interfaces; prototyping and design for manufacturing, environment, etc; patents and intellectual property; and economics of product design.

Sustainable design seeks to reduce negative impacts on the environment, and the health and comfort of building occupants, thereby improving building performance. The basic objectives of sustainability in engineering design are to reduce consumption of non-renewable resources, minimize waste, and create healthy, productive environments. Sustainable product design should focus on all of the four domains: human (manpower) sustainability, social sustainability, economic sustainability, and environmental sustainability.

The PD course could include independent learning assignments and instructor-taught short modules on sustainable design principles and practices. Some of these could be selection of low-impact materials that will promote product longevity; minimize the use of non-recyclable materials, and avoid coupling materials that cannot be recycled; using design techniques such as honeycombing to reduce the amount of material used; capitalizing on renewable energy sources (solar, wind, tidal, hydrogen, etc); focusing on space efficiency; and reducing waste disposal.

Activities and assessments could include group discussions, mini-projects (written reports and verbal presentations), MCQ and TF type questions, case studies, etc. One very good (and commonly available) example of a sustainable engineering product is solar panels for power generation. They can be fitted to buildings of any shape or size, and their installation and maintenance costs are well within the economical rage of ordinary citizens.

In these and other courses where this sustainability education attempt has been made, initial response is encouraging. However, there are concerns from both the faculty and the students about the extra efforts needed.

Engineering Materials Course

The Engineering Materials (EM) course focuses on engineering materials, their properties and use in design or performance enhancement. Topics covered are major classes of engineering materials (metals and alloys, plastics and rubbers, ceramics, composites), their properties and applications in design and manufacturing, and techniques of performance enhancement such as heat treatment. Emphasis is on manipulation of material properties, and use of the Ashby method for material selection. In the modernized curriculum, half of the course would cover the science and engineering of modern materials, and the other half would consist of modern manufacturing techniques.

Following are some examples of topics or short modules that can be integrated into the course from a sustainable development viewpoint. Under steel alloys, introduce the current trend of moving from integrated steel plants to mini-mills, the first using traditional iron ore, while the second starting from iron/steel scrap. For selection of plastics and polymers for engineering products, while explaining the unique or salient features of each polymer family, also discuss the issue of recyclability. Topics such as plastic waste management and related environmental and economic issues can also be included. Introduce recent trends such as green engineering materials, and the reuse and recycling of materials.

The Environment Authority (EA) of Oman, as part of its drive to promote sustainable development, recently implemented a ban on single-use plastic shopping bags. As an independent learning activity, students are asked to read news and magazine articles about this government initiative. Out-of-class activities (and assessment) could include short written report and presentation (group work) on this topic. In-class activities could be individual or group discussions on the importance of this step, expected percentage savings in waste generation, community response, ways to promote sustainability culture in city and village neighborhoods, similar future steps by the government and their pros and cons, etc.

Challenges in Sustainability Education

Sustainability Practice in Academia

The best way to teach something is to practice it. The practice in many academic institutions around the world is quite contrary to sustainability principles. New labs and research centers are established by some enterprising faculty, involving major time, effort, and cost. This faculty member leaves, and the center goes to seed, or at least becomes drastically less effective. New equipment is procured (major cost), but technical staff are not properly trained. Maintenance contracts not signed for critical (and costly) equipment. Replacements for faculty and staff are not planned well in advance. When sustainability is not practiced, and is not an integral part of the culture, how can it be taught effectively?

Policy Making Issues

ABET criteria for accrediting engineering programs [24-26] states that Student Outcomes (SO) "describe what students are expected to know and be able to do by the time of graduation … knowledge, skills, and behaviors." In their earlier (a to k) version, SO (c) was defined as "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability." In their latest revised (1 to 7) version, SO (2) reads as "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors." Sustainability has been removed from the description of student outcomes. Addressing all student outcomes (or graduate characteristics/attributes) in engineering courses requires changes in course objectives, contents, delivery, and assessment. It poses major challenges in implementation worldwide, with stiff resistance from faculty, staff, and administration. If sustainability is not even included in the ABET criteria, its inclusion in engineering education becomes even more of a challenge.

Content Overload

In engineering, an undergraduate degree is generally considered to be the professional degree. Engineering curriculum is therefore already over-full. Inclusion of additional courses requires major overhaul of the whole curriculum. That is why the Center for Sustainable Engineering [27], a consortium of five US universities, target the introduction of sustainable engineering modules in existing courses for any curriculum revision, rather than the development of new courses. In a later section on sustainability based revision of the Mechanical Engineering program at our university, the same strategy has been adopted. Even then injection of substantial new content into existing courses is a major challenge.

Cultural Issues

Many environmental groups and movements, and much of sustainability literature, creates a dynamic that has an anti-technology bias [28]. Predictably, this reduces the interest of practicing engineers and engineering faculty in sustainable engineering. There needs to be focused effort in policy making and nurturing of public sentiment towards sustainable engineering and its effective education, at international, national, and local levels.

Environmental Protection or Sustainability

Many engineering programs now have modules (or full courses) related to green engineering, industrial ecology, pollution prevention, methodologies such as design for environment (DFE), etc. All of these also fall under the umbrella of sustainable engineering (SE). However, inclusion of SE in engineering education involves social and cultural issues, and requires changes in attitude and professional conduct. Environmental issues can be more easily defined and quantified than social or cultural issues, and are more amenable to engineering cultures and frameworks [28]. Also, many of the stakeholders that proclaim sustainable products, actively oppose regulatory compliance and consumer acceptance. Who should decide what is socially and culturally preferable: government entities, consumers, stakeholders, or activist groups? There is another major difficulty with sustainable engineering as opposed to environmental engineering. The skill set necessary to evaluate environmental issues already included in engineering education outcomes. The skills necessary to navigate the minefield of social and cultural attitudes and values, and the inherent conflicts, are not well-defined and generally not a part of engineering curricula.

Conclusions

This work-in-progress paper addresses the why and how of including the critical issue of sustainability in engineering curricula. After a brief overall introduction of the topic, the term sustainable development is explained, and the structure of the paper is described. The relationship between sustainable development and sustainable engineering is explored. The differences between the three very pertinent (and apparently similar) concepts of sustainable, renewable, and recyclable are clarified. The main theme of the paper is discussed through two sections on "education for sustainable development," and "pedagogy for sustainability education." The initial efforts to include sustainability education in the mechanical engineering program at our university are then described. This includes a roadmap for sustainability curriculum, and examples from two courses, Product Design, and Engineering Materials. At the end, some major challenges in sustainability education are briefly examined, such as sustainability practice in academia, policy making issues, overload in curricular content, cultural issues, and the ambiguity between environmental protection and sustainability.

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