Teaching Old Disciplines New Tricks: Sustainable Engineering Education

5

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Abstract

Engineering as a profession unquestionably contributes to the welfare of humanity, yet it is becoming more and more evident that the standard engineering curriculum, a product of the post-World War II era, is no longer optimal for the globally competitive, entrepreneurial firms of the knowledge economy. Further, as engineered systems become more widespread and increasingly coupled with cultural and natural systems, the impacts of new technologies become more unpredictable. Engineering in such a complex and rapidly changing environment requires engineers that are increasingly sophisticated with respect to the challenges of sustainability and complex adaptive systems. Thus, an educational system appropriate for the Anthropocene (the "Age of the Human") is one that builds adaptive capacity into the curriculum itself as well as its graduates. This chapter suggests that a framework – a sustainable engineering method – might facilitate the evolution of engineering education and constitute a structure for imparting competencies to students that will prove valuable and relevant in the twenty-first century. Though it cannot address all issues surrounding engineering education and is therefore not a comprehensive solution, it is meant to serve as a reference for educators as they conscientiously design each curriculum to meet the needs of students, their future employers, and the world at large.

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> *It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change.*
>
> *Charles Darwin*

> *Nothing is permanent except change.*
>
> *Heraclitus of Ephesus*

Engineering is a powerful societal force. As engineers conceive and create the built environment, they inevitably influence social and environmental change. However, a number of groups and individuals have recently expressed concern that engineers do not sufficiently understand the context and implications of their work and that both engineering practice and engineering education have failed to adapt to the needs of a world that is growing in both population and complexity (National Academy of Engineering 2005).

In this chapter, it is not assumed that engineering and its curriculum are failing or need to be "fixed" in any way. On the contrary, modern life in developed economies provides daily reminders that engineers are competent and responsible: Aircraft take off and land safely; potable drinking water is readily available; communication networks are fast and reliable. Engineering is among the somewhat unfortunate professions that go unnoticed if done well. Attention is paid to it primarily when mistakes are made – or when the public becomes disillusioned with the products (or unintended consequences) of engineered systems.

That said, while engineering and its professional preparation may be adequate for the moment (though some dispute this), there is always room for improvement. The goals and paths to improvement are often elusive, however, and that is the topic of this chapter. Hence it will provide an overview of some of the criticisms of existing curricula followed by a discussion of calls for more sustainable engineering practice. Throughout the text, a single framework – a sustainable engineering method – will be offered as an example of one possible path toward a curriculum that meets the needs of a complex and changing world. The goal of this engineering method is to instill several competencies in students, which will be discussed below. Ultimately, the framework remains one of many possible solutions and is itself merely a preliminary concept. Moreover, the focus on incremental improvement presented in this chapter does not obviate the possibility that radical rethinking of engineering education may be necessary and desirable (Allenby 2011).

1 Calls for Reform in Undergraduate Engineering Education

The engineering curriculum as it stands today is largely the product of increased federal funds for science after World War II. As universities hired more professors to conduct research and teach, the number of practicing engineers on the faculty dwindled. Simultaneously, classes that stressed engineering science, theory, and mathematics replaced the design-oriented courses of the 1940s and before (Lattuca et al. 2006). The legacy of this transition is ambiguity as to whether universities are “creating practicing engineers, or pre-professional engineering talent” (Yunhe 2010, p. 118). That is, depending on the school, engineering professors may be primarily focused on research and not able to provide the examples and coaching that a professional engineer would.

This may be the reason that most engineers today undergo two phases of education: undergraduate study followed by apprenticeship. The undergraduate experience is well known for teaching “the basics” underlying the practice of engineering. Then, upon graduation, students generally enter into an apprenticeship or mentoring relationship where they learn about the *practice* of engineering: design processes, industry best practices, how to communicate with clients, etc. In some cases, this apprenticeship may be formal and defined as in graduate school and some companies. In other cases, young engineers may simply take a job where they learn company expectations, methods, and technologies from a manager, through corporate training, or on an ad hoc basis. Whatever form it takes, the value of this largely unspoken and implicit tradition is underscored by the Professional Engineer licensing process, which requires 4 years of engineering practice, typically under the supervision of a licensed engineer (National Council of Examiners for Engineering and Surveying n.d.).

This model might have worked in the mid-twentieth century when engineers stayed at one company for their entire careers, industrial employers could afford such an investment, and when what was expected to be learned on the job was elaboration of skills and knowledge already learned by the student. Today, however, a combination of accelerated turnover, increasing international competition, and rapidly changing technology has rendered that paradigm obsolete. Today’s more nimble and entrepreneurial firms need graduates who already have professional skills and can hit the ground running (Kennedy 2006). Further, employers want well-rounded engineers; they repeatedly emphasize the need to instill good communication abilities, as well as more traditional business skills such as teamwork, project management, leadership, decision making, and assertiveness (Finley 2005; Fischbach 2008). They additionally indicate that engineers of the future will need to foster innovation and be able to manage teams in a global context (Finley 2005; Kennedy 2006). Many of these necessary skills and capabilities are currently not taught well either by firms or by engineering schools. Moreover, to the extent that the skills that are missing are not elaborative, but fundamental – the ability to write well, for example – on the job training is simply inadequate. Good communication skills are a product of years of education, not simply a module of a corporate training program.

So even though apprenticeships are unquestionably valuable, and some on-the-job training will be unavoidable due to technologies, processes, and expectations unique to each firm, this economic environment has presented an opportunity, even necessity, for engineering education to adapt. Thus, in the last decade, a number of groups have called for reformation if not transformation of the engineering curriculum, based in part on the changing needs of the workplace (Grasso and Burkins 2010; Sheppard et al. 2009). Among their recommendations are the introduction of problem- or project-based learning, the hiring of professors of practice as instructors, limited-term appointments (i.e., the elimination of tenure) for engineering faculty, and the development of closer relationships between engineering schools and industry. Others are calling for a more sweeping redesign of engineering education. The National Academy of Engineering has suggested that the engineering undergraduate degree should become a liberal arts degree (a "preengineering" or "engineer in training" degree), with the master's degree constituting the professional degree, similar to medicine or law (National Academy of Engineering 2005). Indeed, it is likely that programs will experiment with multiple strategies as they revamp their engineering programs. It is against this background that one possible seed of a methodology for the professional engineering degree is presented.

1.1 Thinking Like an Engineer

At the end of the nineteenth century, law schools transitioned from away from a lecture-textbook method of teaching and took up the case method, requiring students to take a more active engagement in classes (Stein 1981). Some view this as an evolution away from teaching laws per sé and instead "teach[ing] students how to think like lawyers" (Grasso and Martinelli 2010, pp. 14–15). Whether or not physical laws are analogous to social laws is a matter for debate. Nonetheless, if students are going to enter the workplace "ready to engineer" (Crawley et al. 2007, p. 6), then the challenge for engineering programs in the twenty-first century is to impart the fundamental technical knowledge and skills of their discipline while simultaneously instilling the *processes* of the discipline. That is, teach students how to think like engineers – and, given the time and resource constraints on engineering education as an undergraduate program, winnow the traditional curriculum to make sure this can happen.

Although the ABET Engineering Criteria 2000 standards have resulted in some positive changes (Lattuca et al. 2006), inertia and opposition to curricular innovation mean that most coursework is still limited primarily to solving well-defined problems through the application of specific techniques covered in a lecture and assigned reading (Duderstadt 2010). This has the ultimate effect of creating knowledge silos that are unconnected to each other and are difficult to transfer to the real world. Courses requiring design and synthesis are currently in the minority and may constitute a solution that is both too little and too late.

University of Illinois professor David E. Goldberg (2010) has observed students struggling with seven skills when presented with a real-world senior design project from sponsoring industrial firms. These include the ability to ask questions in order to fully understand the problem and its boundaries, the ability to label the design challenges and associated technology (this may come from a fundamental ignorance of technology despite a demonstrated competence in science and mathematics), the ability to model problems quantitatively (above and beyond routine engineering calculations), the ability to decompose design challenges into smaller subproblems that are more easily solved, the ability to gather relevant data via simple experiments or library visits, the ability to generate ideas and visualize solutions, and the ability to communicate solutions – both verbally and in writing. He suggests that "the basics" of engineering should be reconsidered and perhaps retooled to make thinking skills "more central to the engineering canon" (Goldberg 2010, p. 149).

James Duderstadt, University of Michigan President Emeritus agrees, stating, "Clearly those intellectual activities associated with engineering design – problem formulation, synthesis, creativity, and innovation – should be infused throughout the curriculum," and adds, "This will require a sharp departure from conventional classroom pedagogy and solitary learning methods" (Duderstadt 2010, p. 28). Thus, just as there is an intellectual divide between engineering students and practicing professionals, there is a gulf between existing engineering curricula and those that would promote integration of knowledge and holistic engineering skills (Grasso and Martinelli 2010). The introduction of an engineering method as a central theme in engineering education might be a first step in bridging both distances. In fact, many firms utilize a basic engineering design process. Teaching engineering within a similar framework could ease the transition from student to professional. Within universities, an engineering method could become the scaffold into which existing courses fit. That is, a course on basic kinematics could be expressed as providing modeling and analysis tools whereas a design course would incorporate all steps of the method. As the curriculum evolved, a larger subset of the method could be introduced into more courses.

One final benefit afforded by an engineering method is that it provides a process through which other important skills may be incorporated. Among these are teamwork, communication, creativity, problem definition, lifelong learning, and an active understanding of stakeholder values. The latter three warrant additional discussion.

1.1.1 Problem Definition

As discussed above, much of engineering education involves the repeated working of story problems for which the answers may be found in the back of the book. This approach may provide students with a basis for problem-*solving*, but does not begin to prepare them for problem-*defining*, "one of the most difficult phases of any engineering project" (Grasso et al. 2010, p. 161). Yet, done well, identification of the root problem or client goals can result in elegant and innovative solutions that save time, money, and natural resources. To illustrate the point, consider the case of Stockholm's traffic. Stockholm consists of 14 main islands connected by 57 bridges. In order to facilitate increasing transit into and out of the city, Stockholm approached IBM with the possibility of adding another bridge. Traditionally, the problem would have been defined as, “the built infrastructure is insufficient to support vehicle traffic flow.” However, working together, Stockholm and IBM redefined the problem as, “how can more people be moved into and out of the city while simultaneously reducing traffic jams?” As a result of this change in perspective, a “tax and drive” system was implemented that had the effect of reducing congestion and pollution, and increasing public transportation ridership (Grasso and Martinelli 2010).

Problem formulation has been called the phase “where technological skill meets the uniquely societal demands of restricted budgets, regulatory frameworks, public-private collaboration complexity, public safety impact, historical context, and public understanding” (Grasso et al. 2010, p. 161). Therefore, regardless of the specific engineering method used, great emphasis should be placed on problem definition in engineering schools.

1.1.2 Lifelong Learning

There is an old saying that, when you go to work, you will use exactly 5% of what you learned in school, but you never know which 5% so you have to learn it all. The problem is that a 4-year degree allows insufficient time to cover the ground from which the critical 5% will emerge. Hence, in a full engineering curriculum, many may see an unacceptable tradeoff between teaching specialized knowledge in the classroom, and focusing on thinking skills. This is understandable but may be more appropriate for an environment where information progresses slowly and engineers spend their entire careers with one firm (Christ 2010). However, in the current knowledge economy, information is increasing exponentially, is readily available, and students are likely to have multiple jobs if not multiple careers (Christ 2010). This is not to suggest that math skills and free body diagrams should not be a part of the curriculum, but specialized knowledge in specific disciplines quickly becomes antiquated, and relying on the state-of-the-art analytical tools of today will not serve them well 20, if not 5, years from graduation (Christ 2010). This raises the difficult possibility that much of the current curriculum may be increasingly obsolete, but that many professors may be in a poor position to understand that.

More valuable is the ability to know when learning is required, how to approach the learning, and how to synthesize and apply cross-disciplinary information to the task at hand. Hence the challenge for educators is to provide students not with a foundation of knowledge, but with “the foundation for a lifetime of continuous learning” (Duderstadt 2010, p. 30). Twenty-first century engineers must master the ability to “learn how to learn” (Gallegos 2010).

1.1.3 Cultures, Stakeholders, and Values

Engineering could be thought of as the application of science in service to society. This is a relevant definition for a number of reasons. At a primary level is the distinction between science and engineering. Even though scientists and engineers may work in similar subject areas, scientists strive for objective observation whereas engineers impact the world and, as such, operate in a realm of values (Koshland 2010). Though professional codes of ethics repeatedly underscore a commitment to the public welfare (Florman 1994), and engineers tend to be very ethical people (Allenby 2012), a failure to recognize that not all groups have values that match his or her own – nor even each other's – could result in anger, resentment, project delays, or worse. The engineer should therefore seek out and respect the input of stakeholders, while realizing that even the stakeholders may not agree. Balancing conflicting values and requirements is a difficult task, but a project that conflicts with stakeholder values will not be successful (Allenby 2012).

At a social level, in order to serve cultural groups well, engineers should seek to understand them. In short, the application of science has the potential to greatly improve the welfare of people, "but such technological interventions will not succeed if they are applied in the absence of cultural or social understanding" (Koshland 2010, p. 58). A solution that does not meet the needs of a culture will not be used and will therefore be a waste of resources.

2 Sustainable Engineering

Because the dynamics of natural systems are becoming increasingly dominated by the activities of the human species, some scientists are now referring to the current geological period as the Anthropocene, or the Age of the Human (Allenby 2011). In response, more and more, client requirements are calling for sustainability of engineered solutions. Even if they do not, many professional engineering organizations have added environmental and sustainability considerations to their codes of ethics, compelling their members to incorporate such considerations into design specifications. This is not as straightforward as it seems. Like values, the definition of sustainability varies from person to person and it falls to the engineer to translate those, often abstract, ideals into solutions that actually work in the real world (Allenby 2011). Furthermore, the goals of economic feasibility, social desirability, and environmental preservation (the three pillars of sustainability) are inherently in tension. Yet as the population and the impact of technology grows, the need for engineers who can manage these conflicting goals becomes equally pressing.

2.1 A Systems Approach

Sustainable engineering requires a systems approach to analysis and design (Allen et al. 2008). More specifically, a sustainable approach would define not just one set of boundaries encompassing the system of interest, but multiple sets of boundaries describing different levels of integration and influence (Allen et al. 2008). As shown in Fig. 5.1, these would range from the micro, or subsystem, level and extend beyond the "traditional engineering sphere of influence" to consider the impact of a new technology on society at large (Allen et al. 2008, p. 8).

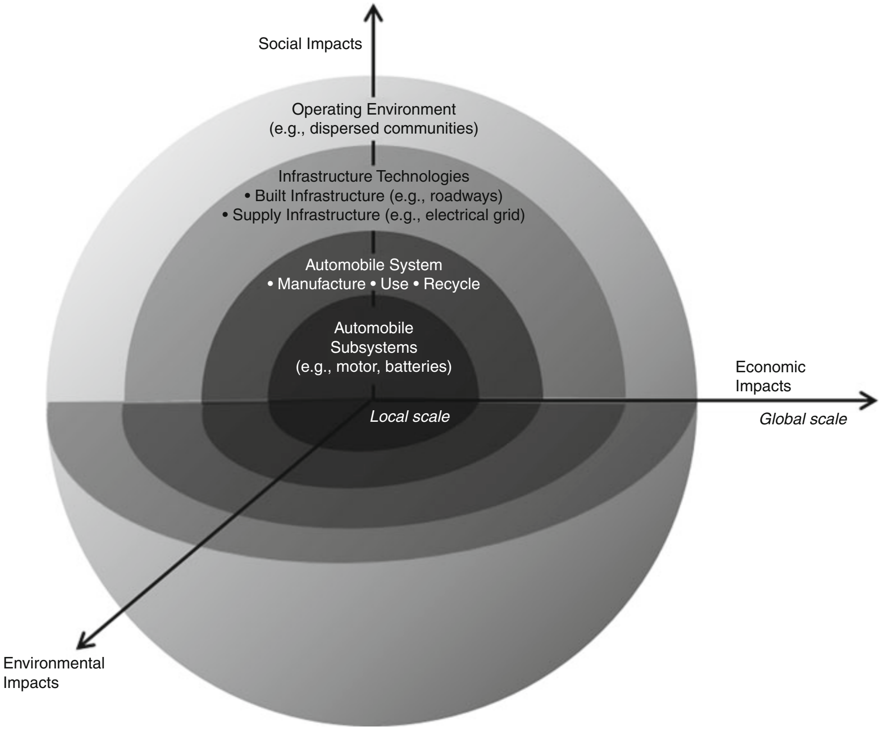

Fig. 5.1 Example of multiple system boundaries for an electric automobile design. The layers are interconnected; changes made at one level affect all others (Based on: Graedel and Allenby 1998)

As an example, consider the concept of electric automobiles. At the subsystem level, lifecycle impacts of nontraditional parts such as batteries should be considered, including the availability of required minerals such as lithium. How would a surge in demand of these resources impact the global markets? At the infrastructure level, the engineer should consider what impact additional loads would have on the electrical grid, as well as the need to add charging stations in parking lots of offices and shopping centers. Finally, at the level of the operating environment, what impacts might electric vehicles have on human behavior? Would the perception of owning a "green" automobile encourage individuals to drive more? Would the relatively short range of these cars encourage people to live closer to their workplaces?

Although they may not currently be prepared for the task, the growing interest in sustainable engineering has tasked engineers with a responsibility for the broader social, economic, and environmental implications of their designs. Otherwise said, good engineering can no longer merely provide a technological solution to an immediate problem; it must challenge itself to consider the larger context, and long-term implications, of the design (Gallegos 2010).

2.2 Complexity and Risk

Just as the layers in Fig. 5.1 are interdependent, they are also coupled with external social, technological, and natural systems. The complex interactions between these systems can result in emergent behaviors that are difficult to predict but can lead to serious consequences (Allenby et al. 2009). For example, the expanded production and use of corn-based ethanol for transportation in the United States in 2007 and 2008 resulted in higher food prices, followed by political instability abroad (Allenby et al. 2009). Thus new technologies, being so integrated into the fabric of society, have both positive and negative impacts, as well, often, as unintended consequences. While engineers cannot be expected to be omniscient, they remain in the best position to consider system-wide impacts and implications. Very often, when deployed on a large scale – perhaps to a global population of seven billion people – solutions to today's problems create new problems tomorrow. Therefore, as part of the normal design process, scenario projection may be employed as one possible means to anticipate unintended consequences so they can be addressed as part of the design (Wise 2010).

3 Toward a Sustainable Engineering Method

Calls for engineering reform suggest the need to introduce an engineering method into undergraduate education but this also provides an ideal framework in which to incorporate sustainability principles. The outline of one such method is presented below and is based on a system engineering methodology provided by Wise (2010, p. 233). However, the development of a method appropriate for a specific curriculum is at the discretion of each individual school and represents a good opportunity to collaborate with industry, government, and professional engineering organizations (Donofrio et al. 2010).

Step 1. Analyze customer requirements. This step should entail asking questions of the client in order to understand their expectations. Moreover, stakeholder input should be actively sought and their values should be understood. In some cases, there will be opposing viewpoints, consider why do these exist and how can conflict be managed. Time should be spent researching the history of the culture, the geographical, and or the issue to be addressed.

Step 2. Define the problem. Do the customer requirements address the actual problem? Are there alternative solutions?

Step 3. Plan the technical effort. Define the boundaries of the system of interest. Identify other systems integrated or coupled with the system of interest and define other boundaries defining larger spheres of influence. Given these coupled systems, identify potential risks associated with the project.

Step 4. Define potential solutions and conduct trade studies. Identify design challenges and conduct research regarding solutions. Brainstorm to generate high-level design ideas. Consider the alternatives in a systemic context and evaluate social implications as well as lifecycle economic and environmental costs. Develop scenarios to highlight possible unintended consequences at micro- and macroscales.

Step 5. Optimize and evaluate alternatives. Further define and evaluate risks; address unintended consequences.

Step 6. Design. If necessary, break the system into subsystems. Develop models as necessary.

Step 7. Verify that requirements were met.

Step 8. Communicate the design to stakeholders. Prepare a comprehensive and easy-to-understand written report and verbal presentation.

4 Summary

Engineering as a profession unquestionably contributes to the welfare of humanity. But as engineered systems become more widespread and increasingly coupled with cultural and natural systems, the impacts of new technologies become similarly unpredictable. Engineering in such a complex and rapidly changing environment requires engineers that are increasingly sophisticated with respect to the challenges of sustainability and complex adaptive systems. The current educational paradigm was appropriate for the world of 60 years ago. An educational system appropriate for today is one that builds adaptive capacity into the curriculum itself and its students. In short, education itself should be a complex adaptive system.

This chapter has suggested that a sustainable engineering method might provide a framework for evolution and suggests a number of competencies that may prove valuable to engineers as they create the twenty-first century world. This is, of course, only a partial solution. Though it will be no easy task, it is up to educators to conscientiously adapt each curriculum to the needs of students and their future employers.

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