

Engineering Design Curricula Review

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Abstract

Engineering curricula are being called upon to respond to changing global economics and increasingly complex societal problems. The design component of engineering curricula is a natural place to address these new realities. As a prelude to examining and revising the design component of the mechanical engineering curriculum at Michigan Tech (and before considering what is needed in the future), we investigated current state-of-the-art in design curricula. Senior design projects are nearly universal on campuses across the country and abroad. To varying extents engineering design is incorporated in the freshman through junior years as well. Current design curricula are expected to achieve many objectives, from teaching a process for solving open-ended problems, to improving communication skills, to serving as a platform for assessing the entire curriculum. Design curricula around the country have many commonalities. This paper summarizes both the commonalities and unique features of engineering design curricula. Many of the objectives for design curricula will remain unchanged as design curricula reform; yet some will shift in priority, and methods for achieving particular objectives will likely change. The paper ends with discussion of what the future may hold.

Introduction

No longer is an engineer associated with pocket protectors and a slide rule. Today's engineers offer an extensive wealth of knowledge in order to apply science, technology, mathematics and practical experiences. An engineer can be described as a problem solver and designer. The application of the design process results in the production and operation of useful products, processes and services. Engineering involves a broad spectrum of specialized subdisciplines that focus on issues associated with developing a specific kind of product, process or service, or using a specific type of technology. Engineers design everything from rocking chairs to artificial organs and prostheses. Becoming a successful engineer requires more than a love for math and science. Because of the wide variety of engineering disciplines and subdisciplines, diverse methods for learning engineering have been developed encompassing both theoretical and practical aspects.

The call for engineering education reform seems to be continuous [1-9]. On the one hand, engineering curricula are slow to change, but on the other hand the target keeps moving. In the 1990's there was a sense that engineering education was out of touch with the actual practice of engineering. In response, design has become a more prominent part of most engineering curricula. In recent years, globalization and the commoditization of many engineering functions has lent an air of uncertainty to the direction that engineering education should go. While entire curricula will likely undergo some revision, it's a good bet that design will again shoulder much of the burden for ensuring the relevancy of an engineering education.

Senior design projects are nearly universal on campuses across the country and abroad. To varying extents engineering design is incorporated in the freshman through junior years as well. As a prelude to examining and revising the design component of the mechanical engineering curriculum at Michigan Tech, we investigated the current status and notable recent innovations in design curricula.

Current design curricula are expected to achieve many objectives, including:

- Introducing students to real-world projects that will attract them to a particular discipline
- Engaging multiple learning styles
- Teaching teaming
- Improving communication skills
- Teaching creativity
- Inculcating the motivation and habit of life-long learning
- Integrating knowledge from engineering science courses
- Introducing business considerations and other systems-level constraints
- Serving as a platform for assessing the entire curriculum

Universities around the country have developed innovative ways to meet the above objectives.

Design Courses

Many universities offer freshman engineering design experiences [10]. Most of these are integrated with other first year courses [11]. Beyond integration with math and science topics, the freshman courses tend to share a number of common goals, including: learning about the different engineering majors, exposure to open-ended problem solving, hands-on project work, development of teaming and communication skills, introduction to the design process [12-20]. The courses intend to excite students about engineering and give them process-oriented tools in support of subsequent courses.

Most engineering departments incorporate some type of senior design project requirement. Engineers design and build systems and objects. Many of the choices made in design stem from qualitative considerations from economic, social, political and environmental aspects. It is hoped that previously developed skills in problem solving, hands-on ability, analysis, communication, and teaming enable students to transition smoothly into senior design projects. Senior capstone design courses share many common features [21,22]. They synthesize knowledge gained during the degree program and they instill professional values such as ethics and societal relevance. Many programs feature industry sponsored projects [23-27] while others feature competitions [24,28]. The ability to work on an interdisciplinary team is becoming a more common goal: Colorado School of Mines, Harvey Mudd, Missouri-Rolla, and Lake Superior State among others have established multi-disciplinary team project courses [29-32].

Design courses in the sophomore and junior years are less common. A sophomore course may be an introductory design course (used instead of a freshman course) [33], or it may expand on a freshman course to further develop problem solving and communication skills [19]. In mechanical engineering programs, a component design course is traditional in the junior year.

Penn State has attempted to improve its relevance by using open-ended design problems to introduce component design topics [34]. Although the courses may not be dedicated to design, some design content has been added to many engineering science courses in the sophomore and junior years. The University of Hartford has successfully incorporated design project work throughout a students' academic career [35].

Hands-On Learning

Students learn by seeing, hearing, acting, reasoning, memorizing and visualizing. A large engineering class may involve students with these learning styles, and more, which requires innovative methods to teach them. Learning styles of engineering students and teaching styles of engineering professors are often incompatible [36]. Most engineering classes encourage students to be passive. Students do not experiment actively or reflect which disables them to learn effectively. Active learning serves as an alternate to lectures [37]. The proof of what is being taught in class is in the fabrication and implementation of hands on experiences. Benjamin Franklin said, "Tell me, and I forget. Teach me, and I may remember. Involve me, and I learn."

Hands-on engineering learning happens naturally in industry settings. Internships and co-ops complement the academic experience and enhance engineering learning. Engineers must stay current with the technological advances in their field. This comes not only by reading and doing sample problems but also by learning firsthand in an industry setting. Internships increase confidence and comfort with engineering, science and scientific research. The feeling of success stems from students working on their own projects and may prompt them to continue in engineering, often serving as an antidote to their possible discouraging classroom experience and grades [38]. The hands-on learning offered by industrially relevant design projects is one solution for engaging more learning styles and improving student retention.

Design studios provide a hands-on environment for working on design projects [37]. Another model for hands-on learning is a "learning factory" that integrates design and manufacturing [39].

Teaming

Working in teams is a vital part of modern engineering education [40]. Teaming is successful in part because of individual processing skills that allow students to communicate and interact with other people in adaptive and contributing styles. It has been found that team learning is effective in promoting greater academic achievement, more favorable attitudes toward learning, and increased persistence through engineering courses and programs [41]. Team members come from different economic, educational and social backgrounds. Individuals bring unique expertise and approaches to the team. Therefore a group of diverse members will jointly have the innovativeness to understand and handle new difficulties in engineering. The benefits of teaming accrue to industry settings as well, and its inclusion in engineering curricula comes primarily at the urging of industry.

Providing the opportunity to work in teams does not necessarily translate into improved teaming skills, however. Seat and Lord [40] developed the following 6 modules for teaching interaction

skills: The Nature of Problem Solvers, Getting Information, Giving Advice, Defending Yourself, Disagreeing Agreeably, and Case Studies. The University of Tennessee experimented with providing a communications coach (who participated in team meetings and provided feedback and direction) to seven “treatment” design teams and found that the treatment teams were more cohesive than the nine “control” teams [42]. A Michigan State program instilled the value of teamwork by assigning each student to both a design team (working on a particular project) and skill team (acquiring specialized knowledge) [43]. Thus, each design team member brought unique and necessary knowledge to the design team.

Gender

Another challenge in engineering education is recruiting and retaining women. The negative impression that many women have of their aptitude for technical subjects is heightened by the traditional instructional mode in college science and engineering courses, which stresses individual work and competitive grading. “What may act as a spur to individual achievement among men is a significant deterrent for women” [44]. Felder, et al. [45] speculate that the observed causes of gender differences in learning engineering have to do with attitudes and prejudices acquired prior to college (e.g. negative beliefs held by both women and men about women’s suitability for technical subjects); some causes involve differences in priorities and goals; others involve a shortage of female role models and mentors in engineering; and still others relate to the instructional methods and the attitudes of professors, advisors and classmates. Design teams offer a potentially attractive learning environment for women students. However, women often play less active roles than men in cooperative learning groups [45]. Educators must therefore stress the importance of valuing contributions from all group members. They may also wish to avoid creating mixed groups in which men outnumber women. More investigations of the effects of team composition on team functioning are needed, however. In one of the few studies involving engineering student teams, Laeser, et al. at the Colorado School of Mines studied the effect of team composition on performance and found that majority male and majority female teams performed better than evenly mixed teams [46].

Creativity and Design Thinking

Real-world problems usually have multiple possible solutions. Central to the design process are the generation of many alternative schemes and the selection of the best one [47]. Design thinking is a complex cognitive process. Dym, et al. remark that good designers are able to tolerate ambiguity, see the big picture, handle uncertainty, make decisions, think as part of a team, and communicate in the several languages of design [48]. Creativity is also recognized as an important part of design thinking. Many approaches have been taken to teach design thinking. Reverse engineering activities have produced positive results [49]. Koen advocates behavior modification strategies [50]. Another approach is to assign a series of open-ended problems and to provide structured guidance along the way [51-53]. Finally, group thinking is improved by forming teams based on learning style or thinking preference indicators [49, 54]. The opportunity to engage in creative activity is attractive to a number of students who might otherwise shun engineering [54].

Communication Skills

Most engineering students take a writing course in their freshman year that is not specific to a technical discipline. However, writing instruction and practice must also be done in a context relevant for the student. In other words, it needs to be integrated with engineering courses. Much of this contextual writing has been placed in design courses, often with writing and engineering instructors collaborating [19]. This placement makes sense, as design teams must communicate information to each other and to an external audience. Newell, et al. note that writing in a design class has three different functions--write to learn, write to communicate, and write to design—and all three need to be nurtured [55]. Wheeler and McDonald observe that writing improves collaboration and critical thinking—both of which are important in the design process [56].

Professional Values

Social relevance has emerged as a focal point for increasing interest in engineering. The reasoning goes that young people want to help people and make the world better. If more realize that that is what engineers do, they will want to become engineers. The popularity of service learning programs supports this reasoning. The University of Buffalo computer science program initiated community based senior design projects [57]. The primary benefit was that students recognized they could positively impact the lives of others. In addition, the projects engaged at-risk students.

Because design is process oriented, it is a natural place to include ethics education [58]. McLean notes that two aspects of the design process invite ethical considerations: identification of criteria and constraints and questioning related to the product life-cycle. Ethics goes beyond concerns for public safety to include consideration of environmental impacts and sustainability.

Assessment

Because senior capstone design classes synthesize knowledge from the entire curriculum, they present an ideal opportunity for program assessment. These assessments tend to focus on design ability and the soft skills, leaving the assessment of technical knowledge to other venues. Developing assessment tools for soft skills or process knowledge is more difficult than for statics or thermodynamics. The faculty at University of Washington developed a comprehensive framework for assessing design knowledge and ability [59]. They identified components (such as problem definition, modeling, communication) of desired knowledge/ability. Then they prepared a rubric of each component based on levels from a modified Bloom's taxonomy. Survey and evaluation questions mapped directly to a cell in the knowledge-level matrix.

Future Directions?

Calls for engineering education reform cite things like innovation, global cultural understanding, and agility as areas of improvement for engineering graduates. The design component of an engineering curriculum is well positioned to address most of these. Innovation and entrepreneurship are emphasized in a special capstone course at University Nevada Reno [60]. An ancillary benefit of entrepreneurship education may be improved retention [61]. U.S.

universities are developing partnerships with universities across the globe, and global student design teams may become a trend. Downey, et al. note that global competency means being able to work with people who define problems differently [62]. They recommend international projects, travel abroad for study/work, and/or an engineering cultures class as ways to help students achieve global competency. While technologies change at ever more rapid rates, the design process remains a constant that engineering graduates can draw on to solve problems. To improve agility, however, engineers must adopt a habit of lifelong learning. Our curricula, therefore, need to evolve to encourage more self-directed learning. Based on their investigation of the types of problems engineers typically solve, Jonassen, et al. recommend that engineering colleges more widely adopt problem based learning (PBL) [63]. One of the principal features of PBL is that student learning is self-directed.

The role of online learning will grow both for on-campus and distant students. Online design learning modules have produced successful results, particularly if they feature interaction [64]. Finally, the rapid pace of technological innovation makes usability and human factors considerations a critical part of the design process [65].

Curriculum Revision Process

There have been significant changes to the design content of engineering curricula in the last 15 years. Required capstone design classes are nearly universal. Early and repeated exposure to the design process is also commonplace. To meet future needs, reforms to design curricula will continue. Incropera and Fox note that the principal barrier to curriculum reform is resistance to change [66]. Most reform efforts begin with the identification of the desirable attributes of an engineering graduate [67]. Faculty members then translate the attributes into course objectives and develop an assessment plan. Finally, course content is developed and implemented, and assessment measures are made. Incropera and Fox note that the reasons for change must be communicated to the faculty before beginning the reform process and then repeatedly over the course of the reform effort. Techniques for engaging faculty, students, and industry in the reform process include: surveys, focus groups, workshops, interviews, regular departmental and area meetings [29,66,68]. An external facilitator may be used.

Conclusion

Design curricula both motivate and teach valuable skills. Design motivates by: engaging students with hands-on, active learning; attracting different thinking styles with its creative aspects; engaging students who prefer collaborative rather than individual work. Design teaches skills such as: an open-ended problem solving process; teaming and communication; consideration of ethical issues. While design curricula have changed considerably in the last 15 years, they will need to change even more to meet current and future needs. There are currently many commonalities in U.S. design curricula. There are also notable innovations in the areas of design thinking development, communication, teaming, societal relevance, and assessment. Future innovations may come in areas such as entrepreneurship, global teams, on-line learning, and human factors.

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