The Role of Open Ended Design Projects in Engineering Education

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Engineering programs represent only a small portion of higher education programs, but the impact of their output on societal welfare is tremendous. Of the 1.3 million students[2] enrolled in accredited programs in Canadian universities in 2015, only 82,000[3] (less than 6.5%) were in engineering programs. However, the influence of engineers is profound in all aspects of society. Their innovations and products are present in healthcare (robotic surgery, artificial implants), the environment (clean water/air filtration), communications (cell phones, broadcasting industry; social media), manufacturing (automotive, light/heavy rail, aerospace), and banking (online banking; debit machines; stock markets), among other areas. While engineers constitute only a small proportion of the total population, the broad application of engineering products affects *all* members of society. The expectations and responsibilities of engineers to address societal welfare needs are significant, and their readiness to identify, synthesize, and solve engineering problems in society is the key to meeting these expectations. The foundation for such readiness must be built through engineering education programs. And because the impact of an engineer's training extends so widely, the quality of engineering education affects us all.

There are two broad types of engineering education programs: content-based programs, and outcome-based programs. **Content-based programs** were developed during the early days of engineering education. The focus of content-based programs is on the knowledge required for engineers to be technically proficient in their field. Traditionally, following completion of these programs, engineers would undergo 6–12 months of training to build the practical skills that would complement the theoretical expertise gained through the program. However, this model was not effective in some countries, particularly where graduates did not have wide access to such training, or industries did not have the resources and flexibility to offering a year-long training term, so graduates entering the work force were lacking practical experience. While this model worked well in North America for some time, companies typically can no longer afford to offer year-long training programs. In its place, the introduction of coop placements has proven to be very effective in developing deeper learning of engineering concepts as well as more practical, hands-on experience. In recent years, the combination of coop/intern placements with traditional learning paradigms has led to the creation of **outcome-based programs**.

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[2] Universities Canada, Facts and Stats: http://www.univcan.ca/universities/facts-and-stats/, retrieved January 2017.
[3] Canadian Engineering Accreditation Board, Enrollment and Degree Awarded Reports: https://engineerscanada.ca/reports , retrieved January 2017.

The focus of outcome-based program is on "what students will be able to know (cognitive), do (psychomotor), and feel/model (affective) by the end of the program or course of study[4]." In addition to the integration of practical training components, the main difference between outcome- and content-based programs is in their connectivity and coherence. In the content-based program, many engineering topics are presented, in the form of different courses, which are disparate and disjointed from one another. In such courses, there is no emphasis on the interactions between subjects. In the outcome-based program, the connectivity between courses is an essential and integral feature. The students, through projects and case studies, use the knowledge from a number of related courses to review real-life cases and build actual products. Through these activities, students gain a deeper and more practical understanding of the subjects, the effect of which is greater than "the sum of the parts" of what they would learn in the individual courses. This holistic training provide students with a wider set of tools to use and a variety of perspectives to consider when faced with a problem. In an outcome-based program, "student learning outcomes catalog the overarching "products" of the program and are the evidence that the goals or objectives were achieved[5]." The program is centered on the notion of an "ideal product." An ideal product may be defined as an individual who has *demonstrated* competence in engineering sciences; who has the *ability* to use appropriate knowledge and skills to identify, formulate, analyze, and solve complex engineering problems with appropriate attention to health and safety risks, applicable standards, and economic, environmental, cultural and societal considerations; and who has an *understanding* of the roles and responsibilities of the professional engineer in society, especially the primary role of protection of the public and the public interest[6]. Most North American and European engineering schools have moved from, or are in the process of moving from, a content-based program to an outcome-based program.

In the context of engineering programs, it is also important to consider the Intended Learning Objectives (ILOs). ILOs are descriptors of the **knowledge**, **skills**, and **values** the students should gain through completion of a given course or program. Knowledge ILOs comprise university-level mathematics, natural sciences (such as physics and chemistry), engineering fundamentals (such as statics, materials, circuits, and thermodynamics), and specialized engineering knowledge appropriate to a given program (for example, machine element design in mechanical engineering; steel structures in civil engineering; robotics and control in mechatronics engineering; electromagnetic fields & waves in electrical engineering; computer network in computer engineering; and process control in chemical engineering). Skills ILOs include the development of effective communication skills, hands-on skills, team work and leadership skills, problem-solving skills for finding solutions to complex and open-ended engineering problems, and, in more recent years, entrepreneurial skills. Values ILOs encompass various aspects of the

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[4] Waterloo Center of Teaching Excellence, retrieved January 2017.
[5] Institutional Research and Assessment, Rensselaer Polytechnic Institute, Student Learning Outcome, http://provost.rpi.edu/institutional-research, retrieved January 2017
[6] Canadian Engineering Accreditation Board, A Guide to Outcome-Based Criteria, https://engineerscanada.ca/.../draft_program_visitor_guide_v1.25.pdf, retrieved January, 2017.

engineer's professionalism in general (roles and responsibilities of the professional engineer in society), and professional ethics, accountability, and equity in particular; as well as analysing social and environmental aspects of engineering activities, and the importance of life-long learning.

The knowledge ILOs of engineering programs that are mainly based on content-based program is outstanding. This is evidenced by the successful performance of engineering graduates of these programs in graduate programs at universities around the world. However, the skills ILOs of engineering schools with content-based program do not achieve the same high standard of the knowledge ILOs. The skills development ILOs would be greatly enhanced by the adoption of more engineering design courses/activities throughout the program, and, more importantly, by incorporating **open-ended design** practise into the curriculum. The values ILOs are out of the scopes of the present article.

The value of design projects, and in particular open-ended projects, can be demonstrated by considering the difference between engineering science problems and design problems. Engineering science problems are problems encountered in engineering text books or similar academic materials. Their characteristics include a well-posed problem; a unique solution with identifiable closure; and a narrow/specific solution area. In contrast, design problems are real-life engineering problems that are characterized as follows: the problem is often poorly posed and ambiguous; the solution is rarely unique; there is no readily identifiable closure; and the solution areas are broad and multi-disciplinary in nature[7]. While engineering science problem solving skills are taught in classrooms, the nature, demands, and ramifications of design problems cannot be taught in lecture halls and must be learnt through experience. Design projects with hands-on practical components are essential for developing the skill set "to conduct investigations of complex problems by methods that include appropriate experiments, analysis and interpretation of data, and synthesis of information, in order to design valid solutions that meet specified needs[5]." Today, engineering design is an integral part of engineering curricula in outcome-based programs. Many engineering programs, such as those across the Faculty of Engineering at the University of Waterloo, have integrated design into their program by incorporating a design project into *each year* of the four-year program. As Richards[8] suggested, design projects stimulate excitement in the students, and provides them with a series of activities to incite creativity and develop real-life problem solving skills. Through design projects, students are able to[7]: "immerse themselves in a domain or problem; generate lots of ideas; use tools for representations and thoughts (e.g., brainstorming); synthesize ideas; avoid premature closure; [learn not to] be afraid to be different; be open and receptive to new ideas; do it; maintain a product orientation; indulge their diversions; reflect and review what they have done; and have a chance to enjoy practising engineering". These advantages are tremendous, particularly among

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[7] Eggert R., Engineering Design, Pearson Education Inc. 2005.
[8] Richards L. G., "Stimulating creativity: Teaching engineers to be innovators," Proceedings of 1998 IEEE Frontiers in Education Conference, 3, 1034-1039.

cultures that prescribe to misconceptions about success – for example, that there is a single, predetermined path that students should follow as they transition from students to professional engineers – which tend to stifle creativity. Hands-on design projects consistently generate excitement in students, as they learn to approach engineering problems in original and innovative ways. Design projects also represent a form of self-education, as they necessitate the application of course content as an outside-of-the-classroom activity[9]. Additionally, as students are faced with a new problem and its associated constraints, they are forced to experiment to find effective ways to learn new concepts. In effect, they develop "learning skills", which not only serve them well during their training as engineers, but can continue to be applied for lifelong learning[10].

Because of the time constraints in a given semester, as well as resource limitations, design projects (other than open-ended design projects encountered in outcome-based programs) are often pre-selected for students and are the same for all students in a cohort. While students gain valuable experience with design syntheses, analysis, implementation, validation, and optimization, these projects lack other critical aspects of the design process: need identification, need assessment, and problem definition. A pre-defined design project has already set the design constraints and defined the design problem, such that the statement of need, evaluation of the need, identification of the limitations of the viable solutions, and generation of problem statement are not required. Students are therefore deprived of the opportunity to transfer a "need' into an engineering design problem by developing a problem statement and developing design constraints and criteria. Such activities can only be offered by open-ended design projects.

An open-ended design project is a project conceived and developed by the student. The project can be based on a "need", normally presented in the form of a statement of dissatisfaction[6], identified by the student. Such a need may be identified through the student's own personal experience, it may be an everyday challenge encountered in society, or it may be an attempt to improve an existing product, based on the student's own idea or an idea proposed by a customer. Once the need is identified, the student uses it as the basis for a design problem. In addition to the statement of need, the inherent components of open-ended projects are: identification of design constraints and criteria, development of a problem statement, and project planning. Through this process, students begin to instinctively examine their surroundings through the critical lens of an engineer, and to take new approaches to solve the problems they identify. They learn "to see the familiar as strange and the strange as familiar on a regular basis, and not rush to spit back a single "correct" solution[11]". "The creativity to envision new solutions to the world's problems[9]" is a key aspect of open-ended design. Open-ended design projects compel engineering students to approach everyday challenges and needs as opportunities to pay service to society by creating solutions to those challenges. They "increase critical thinking; increase

[9] Prince, M. "Does active learning work? A review of the research." J. Eng. Educ., 93(3), 223–231. 2004.
[10] Brydges R., Dubrowski A., and Regehr G. "A new concept of unsupervised learning: Directed self-guided learning in the health professions." Acad. Med., 85(10), S49–S55, 2010.
[11] Sanoff A. P. "Engineers for All Seasons," Prism, 12(5), 30-33, 2003.

self-direction; provide higher comprehension and better skill development; create self-motivated attitudes; enhance awareness of the benefits of teamwork; and provide a more active and enjoyable learning process[12]". Above all, the satisfaction and sense of accomplishment derived from completing a major open-ended design project builds the confidence young graduates will need to tackle large-scale engineering problems as professional engineers.

Final-year design projects (or in some cases undergraduate thesis) present an excellent opportunity to incorporate a major open-ended design project, in which students apply the knowledge and experience gained through their course of study to create a real-life solution. In the process of undertaking an open-ended design project, students also inevitably develop entrepreneurial skills, as they transform their vision for an engineering solution into reality. To augment entrepreneurial skill development, such projects are often accompanied by a major design symposium, where students have the opportunity to pitch their design as a business case to industry experts, entrepreneurs, capital ventures, and accelerator and incubator center representatives. This may lead to students being asked to develop a business case for their product, and allows them to see the opportunities they can seize by taking their design idea to a professional level. Such opportunities give students exposure to and familiarity with the kinds of activities involved in industrial settings in general, and entrepreneurial pursuits in particular. This aspect of open-ended design is particularly important in a place like Iran, where students tend to be reluctant to venture away from academia. The vast majority of students who complete an undergraduate engineering degree in Iran will continue on to graduate studies, with most eventually completing a PhD and working in academia. While the importance of having talented, hard-working engineers in research positions should not be downplayed, a strong research community must exist alongside a thriving industrial sector. Training in open-ended design, and the associated entrepreneurial skills, has a critical role to play in preparing students to take on the most challenging issues facing our societies, whether through research, or through more practical applications, for example, through the private sector.

The millennium generation are the next cohort of engineering students: the majority of students entering undergraduate programs in the 2018 academic year were born in 2000. For most of their lives, game-changing innovations like smart phones, social media, and Google were established norms, and they were raised with the notion of "the next big thing". Social media has exposed them to and connected them with young engineers across the world who have created innovative and disruptive products with globally significant impacts. At the same time, by establishing their own social media presence, they are, in a way, already making a mark on the world. By creating platforms centered on themselves and their interests, young engineers are comfortable with the idea that their voice matters, that their ideas are important, and that they should be "putting themselves out there". Engineering education has an important role to play in fostering the skills they will need to undertake ambitious endeavours. There are many examples of excellent

[12] Johnson, P. "Problem-Based, Cooperative Learning in the Engineering Classroom," Journal of Professional Issues in Engineering Education and Practice, 125(1), 8-11, 1999.

companies that demonstrate what is possible when students of this generation are provided with strong training through outcome-based engineering programs. Canadian companies Thalmic labs (www.thalmic.com), and Clearpath Robotics (www.clearpathrobotics.com) are two such examples: both were born out of University of Waterloo fourth-year design projects. These multi-million dollar companies have had substantial commercial success and are releasing products that are having widespread impacts across sectors. Thalmic Labs is changing the way we interact with our devices, and their wearable tech products have been called "revolutionary[13]". Through their innovative robotic technology, Clearpath Robotics offers automation solutions and a range of services, which are having drastic impacts on defense, mining, and agriculture. Snap and Tap30, a ride-sharing app, are similar successful examples of start-ups by young Iranian engineering graduates, and demonstrate the potential of the talent pool of young engineers in Iran to innovate solutions to the societal challenges they identify. A common attitude of this generation can be summarized by one of our recent Mechatronics Engineering graduates: "if we do not establish our own start-up company to seek solutions to the major needs of society, then we have failed the program we have gone through." This generation is ready to tackle big challenges; the engineering education programs have an important responsibility to equip them with the tools they will need to realize a healthier, more equitable, and more connected society.

[13] David Z. Morris, Fortune Magazine, http://fortune.com/2016/01/25/consumer-wearable-powering-next-gen-prosthetics/, retrieved January 2017