Future Directions in Engineering Education: Educating Engineers of the 21st Century

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Abstract

Engineering schools today are facing challenges they have never faced before to produce graduates who are relevant in the 21st Century. Today's engineers are entering into a world marked by rapid and global change, exponential advancement in information and computer technologies, complex ethical issues, borderless global competition, changing demographics, sustainability, and a multitude of problems that only emerged in the new millennium. Just as business as usual will not survive in the 21st Century, education as usual will also not get us there. This paper briefly explores challenges in global engineering practice in the 21st Century, before laying down the status quo in engineering education. From here, based on numerous engineering education reports that have emerged from various parts of the world, the requirements as well as issues to overcome in educating engineers of the future will be dwelled.

21st Century Challenges in Engineering Practice

The 21st Century brings about major changes in the global environment. Marked by rapid development in technology, explosion in information generation, borderless economic and business operations, issues in sustainability and security, and many other complex, novel problems that have never been seen before, the way businesses, governments, and various entities have to change their modus operandi (NAE, 2005; Duderstadt, 2008). To remain competitive, industries produce over thousands of new products a year that caused the existing products to be obsolete within a short period of time. This gradually put the product development time down, causing pressure on engineers to deliver novel solutions quickly.

Increasing prices of resources, such as raw material and energy, place urgency upon the need for efficient and optimized processes, leaving little room for error. Global competitiveness and the quest for low production cost also result in outsourcing of engineering services to places that can provide the best value for money, turning it to a global commodity (National Science Board, 2007). At the other end of the spectrum, intensive knowledge and high technology research and development activities, a trademark of knowledge economy, are clustered around nations that can provide highly capable, "renaissance" engineers who are innovators with professional skills,as well as in touch withbusiness and community needs.

A study commissioned by the UK Royal Academy of Engineering described in the 2006 report, Educating Engineers for the 21st Century: The Industry View, in the first two years, engineering graduates are involved in all phases of product lifecycle, from research and development (R&D), to design, manufacturing, project management, and even sales. While R&D and design dominate the jobs companies assign to engineering graduates, 15% of the companies surveyed in the study reported assigning graduate engineers roles in sales because they need people who can understand and recommend the correct solution to customers in selling high tech products (Spinks, Silburn and Birchall, 2006).

The need to remain competitive in these demanding times cause many developed nations to invest heavily in efforts to transform engineering education. Engineers, as problem solvers and innovators, are seen as assets to a nation's economy. As stated in the next UK Royal Academy of Engineering report in 2007, Educating Engineers for the 21st Century:

"No factor is more critical in underpinning the continuing health and vitality of any national economy than a strong supply of graduate engineers equipped with the understanding, attitudes and abilities necessary to apply their skills in business and other environments."

Malaysia's desire to materialize a high-income society requires a shift from manufacturing to knowledge economy, as outlined in the New Economic Model. As such, engineering graduates in Malaysia, as the future manpower that drive the nation's economy, have a crucial role in transforming and supporting Malaysia into an innovation and knowledge led economy.

To be competitive and taking role of leadership today and in the future, engineering graduates must have world class engineering education that equip them with the latest technical knowledge and tools, and have adequate understanding of the social, economic and political issues that affect their work. More than ever, engineering decisions affect local communities, be it in construction, manufacture of products (which may be hazardous), automation (cutting down labour), energy source and generation (impact on energy demand versus the environment), waste treatment and many more.

Major recent engineering mistakes that results in catastrophic disasters, such as the Deep Water Horizon explosion in the Gulf of Mexico in 2011 and the Fukushima Daiichi Nuclear Power Plant accident in 2012 showed how costly these mistakes can be to millions of people. Clearly, engineering graduates of today and the future need to understand their ethical and professional responsibilities, not just towards industries, but also towards the well-being of the communities, nation, and the whole world, in general. The extent of challenges faced by future engineers are aptly summarized by Duderstadt (2008), in his report on *Engineering for a*

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Changing World, in the list of Grand Challenges as shown in Table 1.

Table 1: The Grand Challenges

The Grand Challenges	
Global Sustainability	Destruction of forests, wetlands, and other natural habitats Global warming Ballooning global population
Energy	Unsustainable fossil fuel Sustainable energy technologies Alternative energy technologies Energy infrastructure
Global Poverty and Health	Green revolution 1/6 population - extreme poverty Globalization
Infrastructure	Aging infrastructure Urbanization Manufacturing to knowledge services Systems integration

21st Century Requirements of Engineering Graduates

The rapid changes 21st Century requires thatgraduate engineers be equipped with the necessary skills, such as information mining, knowledge integration, ideas creation, and especially problem solving. In an increasing global workplace, engineering graduates are expected to function on multinational and multidisciplinary teams, have global perspective, and to be culturally and linguistically literate (Spinks, Silburn, and Birchall, 2006; Duderstadt, 2008). Industries, such as IBM and Siemens, define the need for "T-shaped" engineers - those with deep knowledge and expertise in their discipline, with a broad breadth of cross-disciplinary knowledge and boundary crossing capabilities, such as an understanding of business context and human as well as social aspects of engineering, communication, systems perspective, lifelong learning skills, ability to innovate, able to adapt to changing environment and requirements and many more. This is also echoed by the Korean government, which stress that engineers who create new technology and knowledge at the local and international level, are the key to a nation's competitiveness (Song, 2012). In order to achieve this, they need engineering graduates who (Song 2012):

- can adapt to open innovation
- are equipped with knowledge and information in their own field, humanities, social science, art, etc.
- proactively respond to changing environment
- are able to interact with at the global level.

Royal Academy of Engineering (RAE) report on Educating Engineers for the 21st Century in 2007 stated that Industries requires graduates with deep understanding of technical knowledge that is underpinned on the fundamentals of the discipline and mathematics along with the necessary thinking (eg critical, analytical and creative thinking) skills and ability to apply the knowledge to real life, as well as professional skills that are essentially enabling skills that allow them to effectively function at the work place, such as communication skills, team working skills, people management skills, etc. The 2006 RAE report defined the "Renaissance Engineer" of the new Millennium (Spinks, Silburn, and Birchall, 2006) as:

- engineer as specialist - engineering graduates as technical experts in their discipline
- engineer as integrator - engineering graduates who can work and manage across boundaries in both technical and organizational requirements of a complex business environment
- engineer as change agent - engineering graduates who can play a critical role as the impetus for innovation in steering the industry towards success and harmony in a sustainable future.

In the later report, the RAE (2007) put forth their finding that the top most quality desired by industries is the ability to apply engineering knowledge to solve real industrial problems. They must be able to take a holistic approach to problems involving complex and ambiguous systems, and to employ creative problem solving skills (Katehi, 2005). The Malaysian Engineering Accreditation Council (EAC), which prescribes to the outcomes based approach under the requirements of the Washington Accord as a member country, requires engineering programmes with the following outcomes in the 2012 Engineering Programme Accreditation Manual (Engineering Accreditation Council, 2012):

1. **Engineering Knowledge**- Apply knowledge of mathematics, science, engineering fundamentals and an engineering specialization to the solution of complex engineering problems;
2. **Problem Analysis** - Identify, formulate, research literature and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences and engineering sciences;
3. **Design/Development of Solutions** - Design solutions for complex engineering -problems and design systems, components or processes that meet specified needs with appropriate consideration for public health and safety, cultural, societal, and environmental considerations;
4. **Investigation** - Conduct investigation into complex problems using research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of information to provide valid conclusions;
5. **Modern Tool Usage** - Create, select and apply appropriate techniques, resources, and modern engineering and IT tools, including prediction and modelling, to complex engineering activities, with an understanding of the limitations;
6. **The Engineer and Society** - Apply reasoning informed by contextual knowledge -to assess societal, health, safety, legal and cultural issues and

the consequent responsibilities relevant to professional engineering practice;

7. **Environment and Sustainability** - Understand the impact of professional engineering solutions in societal and environmental contexts and demonstrate knowledge of and need for sustainable development;
8. **Ethics** - Apply ethical principles and commit to professional ethics and responsibilities and norms of engineering practice;
9. **Communication** - Communicate effectively on complex engineering activities with the engineering community and with society at large, such as being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions;
10. **Individual and Team Work -** Function effectively as an individual, and as a member or leader in diverse teams and in multi-disciplinary settings;
11. **Life Long Learning -**Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.
12. **Project Management and Finance -** Demonstrate knowledge and understanding of engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environment.

Requirements on the programme outcomes by the EAC is obviously geared towards producing graduate engineers with abilities that will match with current and future requirements of stakeholders. The need for graduates to be able to take up complex engineering problems or activities is obviously of utmost importance when six of the outcomes explicitly use the phrase. These outcomes, in fact, is in direct compliance to the Washington Accord's engineering attributes in which all the engineering accreditation signatory bodies must also follow. Based on the findings put forth in the various engineering education reports from throughout the world, this requirement is in-line with the desired attributes of engineering graduates from various research reports as discussed earlier in this section.

Research has been conducted to find out ways to achieve the skills needed by engineers of the 21st century such as in teaching and learning (Fatimah et al., 2012; Mohd-Yusof et al., 2013; Syed Ahmad Helmi et al., 2013; Umi et al., 2013; Mohd-Yusof et al., 2014), curriculum (Mohd-Yusof et al., 2012; Phang et al., 2013) and industrial training (Phang et al., 2014).

Current and Future Engineering Education

Given the current and future challenges in engineering practice, as well as the requirements on engineering graduates, engineering education clearly need to be transformed from the current practice.While technology and engineering practice have clearly changed by leaps and bounds, the way engineering students are taught has hardly changed. Lectures and recipe-type laboratories are very much the predominant method of delivery in engineering education. It is not surprising to hear the numerous complaints from industries and regarding the absence of critical skills among graduates. While it is always easy to complain about the quality of graduates, industries also have a major role to plan in educating engineering students through participation in curricula as well as extra curricula activities. Although transformation is clearly needed, it is not always obvious what engineering education need to transform into, and how to do it.

Based on engineering education reports, a summary of the challenges and the attributes of effective graduates of the 21st century can be seen in Table 2. To get the required attributes, engineering education have to change towards the desired characteristics shown in the last column of Table 2 (Syed Ahmad Helmi, 2011; Duderstadt. 2008; NAE, 2005).With the current state of engineering education, which is rooted in the traditional approach of teacher-centered courses taught in silos with mostly written examinations as the only means to assess students, engineering educators will have to honestly examine the commitment to move engineering curricula (which includes teaching and learning methods used, as well as proper assessment) towards the desired characteristics as shown in Table 2.

Engineering education of the future requires innovative efforts to deliver the required characteristics as shown in Table 2. While program outcomes, in accordance with Outcomes-based Education (OBE) which is prescribed by the Washington Accord, mostly matches the attributes of the future graduates given in the middle column of Table 2, the curricula of the majority of engineering programs, unfortunately, are not aligned to support the attainment of these outcomes. Most program owners choose to take the strategic approach of simply documenting the traditional curricula to suit OBE, rather than embrace the philosophy of OBE to transform the curricula. Assessment and evaluation are taken at a purely mechanistic level to somehow quantify measurements of all outcomes using numbers or percentages, without fully understanding what they mean, as well as their validity. These lofty 21st Century outcomes, however, will just remain on-paper if the delivery and assessment remain as they were as in the 20th Century.

Table 2: The Engineers and Engineering Education of the 21st Century

Challenges of the 21st Century	Attributes of Effective Engineers	Desired Characteristics of Engineering Education
• knowledge economy • globalization • demographics, • technological change • technological innovation • global sustainability • energy • global poverty and health • infrastructure	• Analytical skills • Practical ingenuity • Creativity • Communication • Leadership • Team working • Professionalism • Dynamic, agility, resilience and flexible • Lifelong learners • Function in global economy • Principles of business and management • Ethics	• Learner-centered • Discovery-based or constructivist learning • Systems perspective • Avoid content orientation • Learn how to learn • inquiry-based scientific methods • Team-based problem solving • Prepare engineers into the global economy

In terms of delivery, for example, among the most desired characteristic of engineering education in the future is learner centeredness. Learner centered refers to framing the delivery of the knowledge in a learning environment that takes into account the background, preconceptions (which are often misconceptions), connections to prior learning or existing knowledge of students, as well as difficulties that they go through in learning the new knowledge, and how to help them understand and develop mastery (Bransford, 1997). What is of utmost importance is what students actually learn, rather than what is transmitted by the instructor. Students actually go through an aligned learning process to match the outcome, while instructors facilitate to support deep learning (Biggs, 1996; Biggs, 2010).

There are a range of techniques in varying degrees of learner centeredness to support the attainment of different levels of outcomes. Higher level outcomes, such as the ability to solve complex problems, requires methods that are more intricate to conduct so as to support students in developing the required outcomes. Nevertheless, the current willingness and ability to conduct learner centered methods among engineering academics are rather dismal. Learning does not occur in a vacuum - students cannot attain lofty outcomes on their own without being guided in a supportive environment. Transformation in delivery will also not take place without institutional commitment, support and will. Commitment at all levels are necessary if curricula transformation is to take place successfully.

Today engineering school must take into account that in the future, students will learn in a completely different way (NAE, 2005). Until today most engineering schools have developed curricula by creating scenarios or predicting the problems we expect to face. In doing so, the focus is more on knowledge rather than skills. According to Bransford (2004), curricula based on specific knowledge are built from the bottom up. Engineers whose education is built from the bottom up cannot comprehend and address big problems (NAE, 2005). As mentioned by Katehi (2005), "the future engineering curriculum should be built around developing skills and not around teaching available knowledge. The focus must be on shaping analytic skills, problem-solving skills, and design skills.

Engineering educators must teach methods and not solutions". Jonassen (2006) directed his work "towards design theory of problem solving" to come up with how to prepare our future engineer to solve work place problem. Stroble (2008) urged engineering education researchers to better understand the nature of work place problem solving especially for instructional and educational strategies that heavily utilize problems like PBL. Savery (2006) related constructivism (which is the philosophical view of how people came to understand), to the practice of instruction. He examined problem based learning, which he considered the best exemplars of constructivist learning environment.

The change toward innovative and meaningful curricula is even more important nowadays to attract the current Generation-Y into engineering. With very little exposure to the importance in the role of engineers, and the blame on engineers for major accidents, the Gen-Y do not see engineering as attractive. The high difficulty level of the content, tortuous learning environment with disjointed curricula that is estranged from the actual application in industries, coupled with relatively minimal reward and recognition compared to other fields are driving away the young generation from engineering. It is therefore not surprising to see efforts in developed countries from North America to Europe, parts of Asia (such as Japan, Korea and Singapore) and Australia, to promote engineering from the school level, even introducing engineering concepts and thinking at the primary schoollevel, such as the Inspire Institute under the School of Engineering Education, Purdue University in the US.

Realizing the challenges ahead, there have been concerted efforts among governments and engineering related NGOs as well as institutions to take the lead in providing leadership for innovations in engineering education. Initiatives to enhance the quality of graduates, such as service learning, cooperative programs, global student exchange and summer school programs, design centric curricula, entrepreneurship, professional ethics, problem or project based curricula, a variety of active learning methods, industrial involvement in various aspects of the curricula, etc are among innovations that are being implemented. Nevertheless, there are also calls for innovations to be properly thought out and studied for real, meaningful impact.As stated by Jamieson and Lohman (2012) in the ASEE report, "Innovation with Impact":

If a "grand challenge" for engineering education is "How will we teach and how will our students learn all that is needed to tackle the challenges of today and tomorrow?", then the issue is NOT simply a need for more educational innovations.

Indeed, implementing innovations without taking the scholarly, evidence-based approach can be costly and disruptive for students learning. Care must be taken because changes made in engineering in education will bring about impact on students, be it positive or negative. What is desired are innovations that are rooted on strong educational principles, that are properly studied, and thus evaluated for effectiveness according to the desired outcomes. The study of innovative practices can lead to further improvements in implementation, which can in turn lead to a virtuous cycle of research.

The move for conducting rigorous research in engineering education gained momentum in the first decade of the 21st Century. In the United States, the National Science foundation allotted millions to fund engineering education research, as well as initiatives to train engineering academics to conduct rigorous educational research. The European Society for Engineering Education (SEFI) received similar funding for conducting and training rigorous educational research among engineering academics. The Korean government currently funds sixty nine innovative centers for engineering education, with five hubs to gather and lead the centers under the hub, each with different innovation emphasis to properly implement and conduct research on the effectiveness of innovations made (Song, 2012). At the international level, the Research in Engineering Education Network (REEN) is a world-wide network which aims to promote and support rigorous research in engineering education.

Clearly, attaining the desired quality of graduates depends heavily on academics that design the curricula, teach, and perhaps study innovations made at their own institution. Streveler, Borrego and Smith (2007) classified the levels of academics in engineering education as follows:

- **Level 0** Teacher who teach as he/she was taught
- **Level 1** Effective Teacher who applies accepted teaching theories and practices
- **Level 2** Scholarly Teacher who evaluates performance of students and makes improvements
- **Level 3** Scholar of Teaching and Learning who conducts educational experiments and documents the results in the form of presentations or papers
- **Level 4** Engineering Education Researcher who conducts rigorous engineering education research and publish papers in peer reviewed journals.

While not all engineering educators are required to be at Level 4, the OBE approach requires that instructors can at least be classified to be in Level 2. Since those at levels 3 and 4 will obviously be beneficial to the engineering education community, it is imperative that institutions encourage and reward this type of work, especially in providing a promotion track for those heavily involved in engineering education. This is of utmost importance in enabling innovation with impact in engineering education for developing engineers that are suited for the 21st Century.

Conclusion

The explosion in technological development since the second half of the 20th Century results in rapid changes and novel challenges throughout the world. To remain relevant in the 21st Century, engineering education has to rise up to the challenge and transform the curricula as well as the way engineering students were taught. To attain the attributes of engineering graduates of the 21st Century, engineering education has to match the desired strategies that can produce the desired quality of graduates.

While there are numerous innovations that are being implemented to enhance engineering education, what is of utmost importance is to ensure that these are innovations with impact. This requires proper research into the significance of the innovations, through which others can also learn and follow suit. Just as engineering innovations requires the path of a scholarly approach, innovations for transforming engineering education also can be best determined through systematic scholarly and evidence based approach.

This paper calls all engineering educators to reflect on what have we done in the past, address the current issues and challenges as well as generally make recommendations that requires proper planning and action plans. It must be realized that, business as usual will not be beneficial if we wish to see our next generation of engineers can effectively play an important role in the society at large. Change is inevitable, to stay competitive, there is the need to discover new knowledge and technology through rigorous research and innovation in engineering education. We must be able to prepare graduates that will make new discoveries, bring new products and services, design, and deliver to serve the communities and innovate continually to support the industries. Hence, the fundamental sciences, engineering principles and analytical capabilities of the students should be enhanced through several active learning approaches and use of current tools and technology. Humanities, arts and social sciences are essential for graduates to be creative, explorative and be open-minded. We must also make engineering education exciting, innovative, entrepreneurial, creative, adventurous, challenging, demanding and empower situational environment more that just specifying curricular details. The key success factors to all this is we need to understand and engage ourselves in issues pertaining engineering education, be committed, work in teams and enjoy all the challenges ahead.

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