Advances in Engineering Education

FALL 2021

Innovation, Design & Entrepreneurship in Engineering Education

A.P. LOH

ELLIOT LAW

AND

ANDI S PUTRA
Engineering Design & Innovation Centre
National University of Singapore

EDWIN C.Y. KOH
Engineering Product Development Pillar
Singapore University of Technology & Design

TANG KOK ZUEA

KHOO ENG TAT
Engineering Design & Innovation Centre
National University of Singapore

ABSTRACT

A quick literature survey shows that Engineering education has been undergoing change since more than a hundred years ago, largely due to the needs of industry. The current drive for change is not very different and comes from the perception that Engineering graduates of today are not able to function effectively in the workplace. This is in part due to the rapid development in technologies which in turn drives the evolution in the workplace. The educational imperative is also driven by the need to educate engineers who are able to develop innovative solutions to help make the world a better place. This paper presents the Innovation and Design program (iDP) which the National University of Singapore (NUS) has implemented to deliver a design education that also teaches innovation and entrepreneurship in the context of real world multi-disciplinary problems. The vision of the iDP is to produce graduates with an entrepreneurial mindset, which is achieved through experiential team project-based learning, incorporating design thinking, innovation framework, prototyping and testing, and a foundation for a business enterprise. The iDP is set up as a second major for all students in NUS.

Key words: design, innovation, entrepreneurship

EVOLUTION OF ENGINEERING EDUCATION

A quick search of the literature shows that change in Engineering education has been taking place since the 19th century under the provisions of the Morrill Act of 1862 [1]. At the turn of the 20th century, the Carnegie Foundation for the Advancement of Teaching also commissioned a study on Engineering education which was subsequently published in a book in 1918 [2]. Many of these changes were motivated by the needs of industry. A recount of these changes since the early 1900s, along with the intended outcomes arising from these changes, is given in Table A1 in Appendix A. This set of changes are presented to provide a more complete understanding of the evolution of education in the USA.

Our current pursuit of change is also driven by changes in the industry. Rapid developments in technologies are changing the landscapes in the workplace. At the same time, the world of today is also plagued with problems of over-consumption due to a rapidly growing population, climate changes, and globalization, just to name a few, resulting in the need for innovative solutions to address these issues. Hence the question is how Engineering graduates can be better prepared to respond to these challenges and opportunities, at the workplace as well as in the society at large.

Change continues to prevail as seen through the various reports which have been published. One of the most comprehensive work on transforming undergraduate engineering education (TUEE) [6] was started in 2013 by the American Society for Engineering Education and supported by the National Science Foundation. The 5-phase multi-year review gathered perspectives from industry partners, students, faculty, professional societies and the community. The work in TUEE also draws from The Engineer of 2020 [4] and the 2017/18 ABET accreditation criteria [5]. From the TUEE report, one of the perspectives shared by the industry is that students should be empowered to “do something they’re personally vested in” and offer different solutions to a problem, rather than to follow prescriptive classroom activities. This amounts to a pedagogy similar to project-based learning (PBL) where students work on projects of their choice and apply their knowledge and problem solving skills to determine appropriate solutions. In the latest reform by MIT under its New Engineering Education Transformation (NEET) [7] initiative which commenced in 2017, the focus is around multi-disciplinary projects, encompassing systems thinking and inculcating students with critical learning and thinking skills. More importantly, NEET is also project-centric. It is clear from these two initiatives that we are no longer debating about the balance between theory and practice as the next wave of change but instead the search is on to bring experiential learning to the students and hoping that the realism of their projects will inculcate more than just technical and professional skills. The search is on to prepare graduates with broader skillsets who can exploit their technical knowledge and skills to bring innovations to society. Above all, these graduates need confidence, leadership and critical thinking skills to forge ahead with creativity and innovations. These skillsets are broader than the professional skills as defined in the current accreditation process.

CURRENT GAPS

The imperative for change comes from the perception that Engineering Education has not kept up with the pace of technological achievements over the last few decades to prepare graduates who can work effectively in a work environment that has been shaped by the digital revolution. At the same time, our world is increasingly challenged by issues of sustainability and climate change. The digital transformation has mandated how we work with one another using modern tools while the problems which the world is facing require engineers to innovate and create solutions which are friendly to the environment, socially acceptable, economically viable and equitable. Both these dimensions call for a very different way of thinking and working together.

Open source software and hardware have resulted in abundance of free or low cost modern tools that enable development of new technologies far more accessible. For instance, Arduino, an open source electronics platform, has made electronics development accessible to students of all backgrounds. Engineering education not only has to adapt to teaching and advocating these modern tools to diverse groups of students but it should also embrace entrepreneurial thinking that empowers students to exploit these tools or technologies to disrupt the status quo and create new values to users.

While current students are adept at using social media platforms, do they understand the values that can be harnessed from digital technologies (including data analytics)? Do they have the skills to identify opportunities to innovate and bring value to customers? The digital revolution has also led to multiple pathways for graduates to engage in the workplace. Increasingly startups are the calling of many young graduates. The gig economy [8] also provides an alternative for many who value their independence and flexibility in the workplace.

The phrase "a career of a lifetime" versus "a lifetime of careers" is now the contrast in our expectations of the current generations but yet the educational system as a whole is only slowly coming to the realization that we need to prepare young engineers beyond hard skills but also mould their mindsets to comfortably adapt to a larger landscape at work. Specifically for engineers, we are inherently educating graduates to be problem solvers and makers and this naturally lends ourselves the opportunity for creativity and innovations. But more leadership and critical thinking skills are required to turn opportunities into reality.

While startups are not necessarily the end goal for all graduates, there are particular characteristics of startup founders who are empowered, passionate and confident and hence stand out more than others. Their mindsets are desirable from different perspectives. Firstly, their passion and abilities to identify opportunities are useful for any kind of workplace. Their abilities to learn, re-learn and thrive on their own (confidence), their readiness to embrace failures, their willingness to embark on multi-disciplinary work and to multi-task, their abilities to pull teams together and to communicate across boundaries are all valuable traits which can prepare graduates for a successful career. Many of these skills are beyond the traditional professional skills set by accreditation bodies. Problem solving and communication skills are only one small part of the whole equation. In addition to these professional skills, it is also desirable to inculcate an open and yet critical mind, curiosity, persistence, sense of urgency, self engaging and yet collaborative, and some level of understanding across disciplines. These traits are well aligned with an “entrepreneurial mindset” [9,10].

Many mindset related learning outcomes are better gained through processes and experiences in a student’s learning journey. These processes allow students to internalize their work (understand impact on users), make decisions and make judgement calls (leadership), engage with stakeholders (effective communications), resolve differences (interpersonal skills), take necessary timely actions and control success/risk factors (appetite for failure). Such experiences cannot be gained from sitting through a series of lectures and working on a project here and there. There needs to be real engagement projects like those in the EPICs (Engineering Projects in Community Service) program [11] which started at Purdue University. The realism afforded by such projects carries several values: the opportunity to work with students from other disciplines, the opportunity to grapple with repeated failures and successes, and not least of which is also the opportunity to apply the knowledge learnt in classrooms. A student who has repeatedly experienced these processes will gain outcomes that are described in the affective domain of learning [12]. The affective domain of learning refers to the development of attitudes, behaviours, and physical skills and includes the manner in which the learner deals with learning emotionally such as appreciation, enthusiasm and motivations. These outcomes can be empowering and self-actualizing for the learner.

In the next section, we describe the Innovation and Design Program (iDP) [13] offered by the Faculty of Engineering at the National University of Singapore. This program aims to graduate students with an entrepreneurial mindset. It is now offered as a Second Major to all students at NUS. It was first offered in 2009 to provide a systematic focus on design for Engineering students.

INNOVATION AND DESIGN AT NUS

Over the years, the iDP has been re-envisioned to inculcate an entrepreneurial mindset [9] in all students. It admits both Engineering and non-Engineering students from different faculties on campus. The iDP curriculum takes up 30% of the 4-year Bachelor of Engineering (BEng) degree requirements. The remaining 70% of the BEng program consists of the core Engineering discipline and general

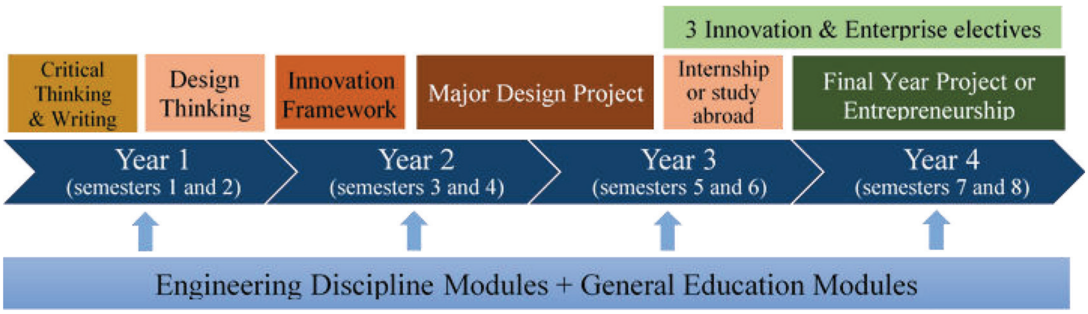


Figure 1. The iDP Curricular Components.

education modules. Figure 1 shows the iDP curricular components which are read alongside Engineering discipline and general education modules offered by the respective Engineering departments.

Students sign up for the iDP in either semester 1 or 2 of their year 1 of study and they read 1 module from the iDP program in each semester as they progress through the 4-year journey in their BEng. The modules which are required of iDP students are given in Table 1 below, along with their expected learning outcomes.

Table 1. iDP Modules with Expected Learning Outcomes.

Modules	Semester of Study	Expected Learning Outcomes
Critical Thinking & Writing	1	Practise in reading and thinking critically. Demonstrate skills in writing. This is a requirement of all Engineering students.
Design Thinking (DT)	2	Applying DT tools to identify "How Might We" design statements to identify problems and explore solutions for a target user group.
Innovation Framework	3	Understanding the innovation framework encompassing ideas of desirability, feasibility and viability. Students learn CAD tools to support concept visualization. Team mates are frequently changed to get them used to working with peers across different backgrounds. Peer assessment takes place in project presentations.
Major Design Project (MDP)	4 and 5	Learn the engineering design process. Apply DT skills to identify design statements. Apply engineering design skills to conceptualize solution and develop proof-of-concept (POC) solution.
Final Year Project	7 and 8	Analyze and evaluate original POC solution from MDP. Re-design better solutions.
Or		Or
Ideas to Startup Module		Learn how to start an entrepreneurial journey. Identify market gaps, iterate on solutions, product re-design, propose business model, product pitching to potential investors.
Innovation and Enterprise (3 modules)	Any semester when they are ready	Modules offered by the School of Business or Department of Industrial Systems Engineering & Management to support understanding of organizations, business management, marketing, venture creation or finance.

The pedagogical approach in delivering the iDP includes studio teaching and project based (experiential) learning with students working in multi-disciplinary teams, immersing the students in a setting similar to working professionals in the field [14]. This mode of teaching enables students to interact with one another to communicate ideas, and constantly allowing for active engagement of learning. The first module on critical thinking and writing is a module which all Engineering students read and it is taught by faculty members from the Communications and English Language Centre. It gives all students some foundation and practice in critical reading, thinking and writing. The Design Thinking (DT) class is unique to iDP and is conducted in groups of 20 to 30 students in studios and students work on projects within a theme e.g. waste reduction, enhancing campus dining experience. The third module gives students an understanding of the innovation framework which encompasses desirability, feasibility and viability, building on their knowledge in DT and some engineering skills. A two-semester major design project (MDP) then follows where students apply the tools of DT, engineering knowledge and design process to devise a solution to solve real world problems. Many MDP projects are derived from partnerships with industries including hospitals, airports, local companies, etc. Some are student initiated projects and yet another category involves designing complex engineering systems with or without a competition component. For example, every year the FSAE (Formula Society of Automotive Engineers) race car team designs and builds a car which competes in a competition in the USA while our satellite group develops cubesats for launch every 3 to 5 years. At the end of the MDP, students may go away on student exchange abroad or participate in an internship. They return to campus in their 4th year to complete either a final year dissertation project (mostly technical and continuation of their MDP) or they can read a module called “Ideas to Startup” (ItS) which takes them onto an entrepreneurial or pre-accelerator journey. Students in ItS are expected to re-discover the market potential for the prototype that they have developed in the MDP. They are taught to look for beach head markets, propose business models, identify financial sources and pitch to investors. This is a unique module which is adapted from Stanford’s Lean Launchpad course [15] and MIT’s Disciplined Entrepreneurship [16] courses. Finally, in order to support the whole experiential learning journey in innovations and design, students are required to read 3 elective modules from a basket of innovation and enterprise modules such as Engineering economics, venture creation, finance and marketing or other similar modules offered by other Departments.

The ItS module started only in 2018 with about 20 students in each cohort. Thus far, it has resulted in one startup (working on providing video analytics for safety inspection in construction worksites) being formed while two more groups in this current batch of students are considering incorporating their companies after graduation. One of these groups has already secured some seed funding to develop their product. Even before ItS was developed as a module in the iDP, there were other iDP graduates who are founders of startups. The most notable of these is a company called TinyMOS which started in 2016 and has since raised more than SGD 4M in total. Yet another startup is called NUSpace which deals with satellite technology and its mission is to provide Internet-of-Things services for the underserved communities.

The essence of the iDP in supporting the development of an entrepreneurial mindset is an ecosystem with mentors, problem owners and maker spaces that allows students to explore their own projects, understand context (DT comes into play), consider impact on stakeholders, design a minimal viable product that solves a problem for a group of stakeholders and finally to embark on a pre-accelerator pathway to conceptualize a startup. The pre-accelerator gives them a tangible "ideas to startup" journey where they experience the need to be multi-disciplinary, multi-tasking, self-actualizing and collaborative. While it is still a long shot from a startup journey with real financial risks, we hope they have experienced the uncertainties involved and appreciated the need to be persistent in the face of difficulties and failures. The learning components built around a real projects are also opportunities for critical thinking and leadership.

The iDP currently has an intake of about 10% of the Engineering cohort (150 out of total yearly intake of 1500 students) at NUS. Forty percent of iDP students come from the Mechanical Engineering Department, 20% from the Electrical and Computer Engineering Department, 15% from Biomedical Engineering while the remaining 25% are from the other Engineering disciplines, with a small handful from non-Engineering backgrounds. In the major and final year projects, students work in groups of 3 to 5, with at least two Engineering disciplines in each team. Approximately 20% to 30% of each cohort of students are involved in building two race cars, autonomous underwater and surface vehicles and satellites (cubesats). The rest are involved in projects with hospitals, government agencies and private companies. One good example of a project with a local hospital involves students developing an automatic way of identifying surgical tools to track the usage of such tools and to account for them at the end of a surgery. Another project was about creating a system to track hospital consumables in the pharmacy and to alert managers when a particular consumable inventory is running low. In a project with the community, students designed an electrical power unit which can be fitted onto a manual wheelchair to turn it into a low cost motorized wheelchair. A current project with the public sector involves designing a floor inspection robot to determine the quality of the floor in terms of floor flatness and levelness.

Regarding exposure to entrepreneurship, every student is required to read at least 3 modules related to innovation and enterprise. This forms the baseline for all iDP students to have some understanding of enterprise development. In addition, 15% of iDP students intern in startup companies in the NUS Overseas Colleges [17], while another 15% signs up for the Ideas to Startup module in their final year.

Many programs in innovation and design are offered at the graduate level. For example, the Carnegie Mellon University's Integrated Innovation Institute [18] offers three 1-year Masters programs which are integrations of engineering, design and business. At the undergraduate level, the University of California at Berkeley offers a certificate program in design innovation [19]. This program has a requirement of 4 courses : a foundation, two design skills and one advanced design. As can be inferred from the course requirements, the program's focus is mostly in design and little about entrepreneurship. Likewise, the Masters in Engineering in Design Engineering [20], offered by the Imperial College, London, focuses more on design engineering but little on entrepreneurship.

The uniqueness of the iDP comes from the point that it is a substantial program offered at the undergraduate level. Students are exposed to real world design problems, while they are still developing their engineering skills. This context is important because it offers an experiential learning environment in which the lessons learnt go beyond engineering. Ideas of desirability in design and viability in the business sense are imbued in students as early as their second year of study. In embarking on a difficult design problem, they search deeply for solutions and learn to deal with setbacks and frustrations. They interact with stakeholders, component vendors and laboratory technicians throughout the course of their projects. We hope that these are learning opportunities that will shape their own outlooks after they graduate from NUS.

CONCLUSION

Engineering education has seen changes as far back as the 19th century. Historically, these changes have been driven by the need to produce graduates who can be effectively employed immediately after graduation. As the employment landscapes change due to technological and social innovations, we continue to see the need to evolve Engineering education, in terms of pedagogies and learning outcomes. At the National University of Singapore, the Innovation and Design program aims to inculcate an entrepreneurial mindset, through opportunities for students to learn about innovation and design in a real world context and to bring their designs to the marketplace. Students learn to define problems relevant to a user group, ideate for solutions using the design thinking process, prototype using their Engineering skills, identify a beachhead market, draw up business plans, and pitch to investors. We hope that in the process of going through all the learning components, students have experienced and developed some skills in critical thinking, team work, communications, project management including managing failures and uncertainties, multi-disciplinary work, and knowledge in creating an enterprise.

REFERENCES

[1] M. Issapour, K Sheppard, "Evolution of American Engineering Education", 2015 Conference for Industry and Education Collaboration, American Society for Engineering Education.

[2] Charles R Mann, "A Study of Engineering Education", The Carnegie Foundation for the Advancement of Teaching, 1918.

[3] Crawley, E.J. Malmqvist, S. Ostlund and Brodeur, D. "Rethinking Engineering Education, The CDIO Approach" 2007 Springer New York.

[4] The Engineer of 2020 : Visions of Engineering in the New Century, 2004, The National Academics Press

[5] 2017/18 ABET accreditation criteria : https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2017-2018/

[6] Transforming Undergraduate Engineering Education (http://tuee.asee.org/about/)

[7] New Engineering Education Transformation (https://neet.mit.edu/about/)

[8] The Characteristics of those in the Gig Economy, Final Report, Department of Business, Energy and Industrial Strategy, UK, February 2018.

[9] The Entrepreneurial Mindset, The Burgess Institute for Entrepreneurship, Michigan State University (https://entrepreneurship.msu.edu/the-entrepreneurial-mindset/)

[10] KEEN Engineering Unleashed (https://engineeringunleashed.com/about.aspx)

[11] EPICS at Purdue University, (https://engineering.purdue.edu/EPICS)

[12] Krathwohl D.R., Bloom B.S. and Masia, B. B. (1964). "Taxonomy of educational objectives, Book II. Affective domain", New York, NY. David McKay Company, Inc.

[13] Innovation & Design Program (https://www.eng.nus.edu.sg/idp/academics/overview/)

[14] Gillies, R.M. (2017). "Promoting academically productive student dialogue during collaborative learning", International Journal of Educational Research, in press. Elsevier.

[15] Stanford's Lean Launchpad course (https://stvp.stanford.edu/blog/stanfords-lean-launchpad)

[16] MIT's Disciplined Entrepreneurship course (http://www.d-eship.com/)

[17] NUS Overseas Colleges (https://enterprise.nus.edu.sg/education-programmes/nus-overseas-colleges/)

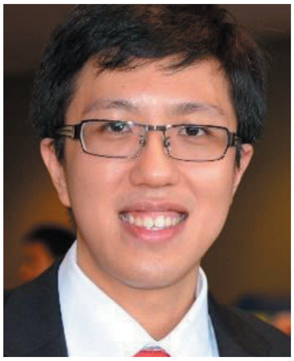
[18] CMU Integrated Innovation Institute Masters Programs (https://www.cmu.edu/iii/degrees/)

[19] Certificate in design innovation at UC Berkeley (https://bcdi.berkeley.edu/curriculum/)

[20] Master of Engineering in Design Engineering, Imperial College, London (https://www.imperial.ac.uk/study/ug/courses/school-design-engineering/design-engineering/)

AUTHORS

A. P. Loh is currently the Director of the Innovation & Design Programme at the National University of Singapore (NUS). She received her BEng (Electrical, First Class Honours) degree from the University of Malaya at Kuala Lumpur in 1983, and her DPhil from Oxford University, in 1986. From 1986–1989, she was with the University of Auckland, New Zealand, first with a postdoctoral fellowship followed by a lectureship. She has been a faculty member at NUS since 1989. From 1994 to 1997, she was a visiting scientist at the Massachusetts Institute of Technology, USA. She was also the Deputy Head of the Department of Electrical and Computer Engineering, NUS, handling the undergraduate programmes from January 2005 to December 2013.



Elliot Law is a Senior Lecturer in the Innovation & Design Programme at the National University of Singapore. With a background in Civil Engineering, he supervises a wide range of student projects, in particular those that are related to smart and sustainable cities. He is currently overseeing a number of projects on smart construction, building inspection and maintenance, work automation, and sustainable living in collaboration with a few industry partners.

Andi Sudjana Putra is a Senior Lecturer in the Innovation & Design Programme (iDP) at the National University of Singapore (NUS). He is one of the founding members of the iDP. At NUS, he leads a Learning Community in Design-Your-Own-Module, exploring Flexible Learning, Community of Inquiry and Students as Partner framework in education. He advises social enterprises and agencies in applying Design Thinking to promote innovation. His research interests include design and innovation in healthcare technology, and he brings his research into the classroom through teaching Design Thinking, Robotics and Design Projects. He earned his Ph.D. in Electrical and Computer Engineering from NUS. He earned his Master of Technological Design from NUS and TU/e (Eindhoven) and his B.Eng. in Mechanical Engineering from Brawijaya University (Indonesia).

Edwin Koh is currently a Senior Lecturer at the Design and Artificial Intelligence Programme and the Engineering Product Development Pillar, Singapore University of Technology and Design (SUTD). He was a faculty member at the Innovation and Design Programme, National University of Singapore, for 8 years prior to joining SUTD. Edwin's research focuses on the design of engineering products and systems, with an emphasis on managing complexity and enhancing creativity. His work appears in journals such as Research in Engineering Design, Journal of Engineering Design, and Design Studies. Edwin received his B.Eng. in Mechanical Engineering and S.M. in Manufacturing from the Nanyang Technological University. He attended the Massachusetts Institute of Technology as part of his master's studies and holds a Ph.D. in Engineering Design from the University of Cambridge.

Tang Kok Zuea is presently a Senior Lecturer in the Innovation and Design Programme at the National University of Singapore since 2010. He received his Bachelor of Electrical Engineering (1998), Masters in Electrical and Computer Engineering (2000) and Doctor of Philosophy in Electrical and Computer Engineering (2005) from the National University of Singapore.

Khoo Eng Tat is a Senior Lecturer in the Innovation and Design Programme at the National University of Singapore. He is an educator and researcher in immersive reality (VR/AR/MR), human computer interface and technopreneurship. He is the module coordinator and lecturer for EG4301A Ideas to Startup final year pre-accelerator module and supervises many immersive reality projects. He is also a startup mentor at the Singapore Infocomm Media Development Authority and Startup SG Network.

APPENDIX A

Table A1. Change in Approaches to Engineering Education and their Outcomes.

Approximate Periods	Approach to Engineering Education	Outcomes
Prior to World War I (1914–1918)	Apprenticeship based education	Produced good practical engineers who can join the workforce immediately
After World War II (1939–1945)	Tilt towards more mathematics and science in the curriculum	Produced engineers who have a better understanding of how things worked.
1950s and 1960s	Incorporation of mathematics and science intensified. Practical work pushed to the higher years of study in Engineering.	Produced engineers with a better understanding of how things work. Approach largely supported research which was attracting grants from industry and government agencies.
1970s	Problem and Project-based learning [PBL] emerged.	Produced engineers with some professional skills related to teamwork, project management, self-directedness and problem solving
1990s	Push to re-introduce more practical aspects of engineering into curriculum. Accreditation process started to re-emphasize design and to re-balance science and practice. The Conceive, Design, Implement and Operate (CDIO) framework [3] was proposed to emphasize the equal importance of technical know-how and professional skills.	Produced engineers with better understanding of the integration between theory and practice. Professional skills given more emphasis.
Early 2000	Framework from The Engineer of 2020 [4]	Outcomes of ABET criteria 2017/18 [5] and prior – still heavily focused on balance between theory, practice and professional skills.