AAEE2018 CONFERENCE
Hamilton, New Zealand

A novel approach to professional empowerment of engineers

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STRUCTURED ABSTRACT

CONTEXT
The engineering design process can be broken into Innovative Conceptual Design (What will we build?) and Technical Design (How will we build it?). Until about the 1980's, technical design provided the binding constraint on virtually all engineering. Consequently, technical excellence was the primary measure of engineering graduates. With more readily available access to large computing resources and high-level engineering software, the emphasis has moved, and Innovative Conceptual Design skills have become relatively much more important. Consequently, to ensure better employment outcomes, engineering graduates need skills associated with Innovative Conceptual Design, such as an understanding of innovation processes, interpersonal skills, appreciation of the benefits of diverse viewpoints, and a self-actualising mindset.

PURPOSE
This paper will describe a new subject at Melbourne School of Engineering, Creating Innovative Engineering. It aims to teach students about the innovation process, how to work in teams, how to work with people with different worldviews, and also to assist students to empower themselves.

APPROACH
- We solicit innovation challenges from sponsors, inside the university and out.
- The sponsoring organisation provides an innovation challenge for students to work on.
- A mentor from the sponsoring organisation comes into the classroom and works with a team of 5-6 students for the semester. The mentor is generally close in age to the students.
- The students go out and interview users/customers to gain insights to drive their ideas.
- During the semester, students are given instruction in "design thinking" methodologies and how to work in teams**.**

RESULTS
Even though the subject is still in its early developmental stages (we have only taught it three times), we have the following indicators of success:
- It is popular with students, and a significant proportion describe it as the best subject they have taken.
- Sponsors generally choose to return in subsequent semesters.
- Some mentors recommend the experience to their friends and colleagues.
- Some students have been hired from the subject, and several projects have been developed further for implementation.

CONCLUSIONS
Inclusion of real-world projects in the classroom leads to high levels of student satisfaction and can give students an appreciation of the challenges in real-world innovation and conceptual engineering design. Implementation of the subject is not without challenges, however.

KEYWORDS
Industry engagement, team-based learning.

Introduction

Design is arguably the central process in engineering. While the design of products, processes, and infrastructure comes to mind, design is much more pervasive to the profession. Engineers design organisations, services, tender responses, maintenance schedules, and so forth.

The Oxford Online Dictionary defines design as “The art or action of conceiving of and producing a plan or drawing of something before it is made.” (Oxford Online Dictionary, 2018). Note that the definition describes design as comprising two acts, “The action of conceiving of something before it is made.” and “the action of producing a plan or drawing of something before it is made.” We will describe the first action as conceptual design and the second as technical design.

Technical and conceptual design in engineering education.

The traditional engineering syllabus focuses on technical design. Engineering students start with foundational subjects (mathematics, physics, chemistry), move on to the core technical design subjects (fluid mechanics, circuit analysis, modelling etc.) and finish their degrees with advanced technical subjects, various subjects that will allow them to apply their technical design skills (law, use of codes, engineering management, etc.), and an array of capstone projects and internships.

For example, the syllabus for one typical engineering course at an Australasian University comprises five parts: (a) engineering fundamentals and foundation skills, (b) engineering design, (c) engineering knowledge and application, (d) professional practice, and (e) electives. The three design subjects that make up part (b) teach students about the technical design of structural and mechanical systems, electrical and chemical systems and software. Likewise, the engineering knowledge and application and professional practice and elective subjects are overwhelming concerned with technical design, its underlying science, or the practicalities of delivering it. Students hardly encounter conceptual design before their advanced electives.

It is no surprise that the syllabus is overwhelmingly about technical design. Technical design has always been central to engineering. In fact, for the first 4,000 years of the profession, engineers’ capabilities in technical design provided the binding constraint on the possible. Famously, the great gothic cathedrals were built by trial-and-error (Courtenay, 1997), and it is often written that the Romans required the builder to stand under an arch when the scaffolding was removed (though this may well be apocryphal). More recently, the Sydney Opera House took 16 years to build because the engineers didn’t know how to build it (Murray, 2003), and the Westgate Bridge collapsed because of inadequate technical design for construction (Barber, 1971).

Each innovation in mathematical technique – the number zero, calculus, logarithms, slide rules, mechanical calculators, mainframe computers, mini computers, third-party packaged software, personal computers, artificial intelligence – expanded the technical possibilities in engineering. Engineering practice grew accordingly.

There have always been aspects of engineering that have not been constrained by technical design. Consider the design and construction of suburban subdivisions. There, budgets, or geography, have provided the binding constraint. Engineering in these areas has generally been low status and relatively poorly paid (U.S. Bureau of Labour Statistics, 2018). The engineers haven’t added much value, and consequently have not been rewarded well (Hickson, Hinings, Lee, Schneck, & Pennings, 1971). However, in the high value-added areas of engineering, the binding constraint has often been the limits of technical design. Not surprisingly, the engineering schools, especially the elite ones, have trained engineers to sit at the technical cutting edge.

The increasing importance of conceptual design

In the 1960s and 1970s, software languages went from being attached to particular proprietary operating systems to being generic. For example, engineers could port their Fortran programs from an IBM mainframe (Fortran was developed by IBM) to a Vax or a Personal Computer. Then, with the development of Mini Computers, and then Personal Computers, third-party applications that made engineering calculations much easier became available. These packages included spreadsheet programs, calculation aids, computer-aided design, drafting, and manufacturing packages and finite-element and finite-difference-based dynamic modelling tools.

These changes dramatically increased the technical power of engineers. For example, as a Summer student in the early 1980’s, the first author spent several weeks checking the dimensions of the irregular precast beams for a bridge. The same calculations could be completed now in an afternoon using a spreadsheet. However, you wouldn't bother to check them now; CAD packages don't make mistakes. Likewise, the flood models he deployed on an HP9845 computer as a young graduate took 27 hours to run. They now run essentially instantaneously.

However, the changes did not just make existing technical design easier, faster, and cheaper. They also pushed back the technical limits on design. This is illustrated most visually in the architecture of Frank Gehry. While the engineers of the 1960s could not work out how to build the Sydney Opera house, today's engineers can design and build Gehry's creations with little difficulty. All engineering disciplines offer similar examples.

Our central contention is that in about 1980, a much more significant event occurred. Engineering practice started to change. As we noted in the introduction, design comprises two parts – conceptual design and technical design. Until about 1980, most engineering was technical-design limited and so conceptual design was the province of experienced senior engineers. For example, the senior engineers would think through how to build a building, machine, or device, or a novel way of constructing a project when writing a tender. Alternatively, senior engineers would work with professionals in other domains (architects, manufacturing managers, logistics experts) to ensure that designs were technically feasible. Engineers would learn the conceptual design skills they needed, on the job, as they matured professionally.

However, the dramatically reduced cost and increased ease of technical design allowed three changes to the way engineers work. It increased the proportion of design time devoted to conceptual design; it changed the design process, and in so doing moved the locus of engineering value creation from technical design to the intersection of technical and conceptual design, and consequently changed the way engineers worked; it changed the structure of engineers' careers.

The changing proportion of conceptual and technical design

At the simplest level, the argument here is a purely logical. If the cost of technical design goes down, then the proportional cost of conceptual design goes up – all else being equal. We can embellish the point a little by highlighting that large purely technical tasks can easily be outsourced to low-wage countries, tilting the balance further. We have seen this most dramatically in software engineering, but it also occurs in other domains.

However, as a senior consulting engineer pointed out to the first author, this has a big impact on engineers' careers. In particular, rather than spending five or ten years "on their tools", slowly learning how to do conceptual design, engineers are now required to actively add value to conceptual design discussions within twelve months of graduation. An increasing proportion of engineering work involves working out how to add value for a client, rather than simply implementing the solution. Consequently, engineers need the ability to do this much earlier in their careers. This is not just a timing issue. It is also a training issue. There is no longer the time to learn these skills by osmosis, and the automation and outsourcing of technical work means that there are fewer osmotic learning opportunities available to young engineers. For junior engineers to start their careers productively, they need to be well-positioned to contribute to conceptual design discussions on graduation.

Changing the design process

Traditional engineering design methods are predicated on the assumption that conceptual design is relatively cheap and technical design is relatively expensive. Consequently, a conceptual designer (architect) would conceive of an engineered product or service and "throw it over the wall" to a technical designer, who would "throw it over the wall" to the person who would build it. Piore and Sabel (1984) note that this separation of conception and execution is fundamental to Fordist mass production, which is predicated on the assumption that technical progress occurs by increasing the division of labour (Marx, 1973).

In the 1980s, with the rise of Japanese and European manufacturing, researchers and practitioners started to realise that the separation of conception and execution was not necessarily optimal, and that closer collaboration between labor and engineers would add value by facilitating organizational learning (Dertouzos, Lester, & Solow, 1989). The organisational learning involved reconceptualising parts of the production process. This insight rapidly expanded to include the idea that the voices of other stakeholders should be incorporated into the design process (Dertouzos et al., 1989). That is, analysts saw the need to incorporate conceptual design into tasks that were previously considered purely technical. Consequently, employers started to look for different skills in the engineers they recruited, particularly the ability to work in teams and the ability to work with and understand people from different disciplinary and cultural backgrounds.

The next major innovation in the design process came 20 years later as the cost of technical design fell. Starting in computer science, practitioners realized that the relative cost of technical design had dropped so far that it was feasible to simply throw out and redo technical designs as a way to build conceptual understanding. Consequently, instead of conducting the design process as a “waterfall’ in which one stage was completed before the next began, teams would build software products in an “agile” manner in which they iterated between conceptual and technical design (Beck et al., 2001). Agile methodologies have spread from software to entrepreneurship (Ries, 2011) and other areas of engineering practice where the benefits of iterated conceptual design exceed the cost of redoing the technical design. Interestingly, agile methodologies change the way technical design is understood. They explicitly place it in the service of value creation for the client, rather than it being an end in and of itself.

Changing careers

The reduced cost of technical design, along with other broad related forces, has had a third effect. Jobs are now much less stable. A generation ago, young engineers joining a large organization could have two reasonable expectations. First they could expect that, as they climbed the organisation’s technical ladder, they would be doing work similar to those currently above them on that ladder. Second, they could expect that the organization would exist, in approximately the same form, at the end of their careers. Neither is now true. The rate at which organisations rise and fall has increased and, more importantly, the jobs within those organisations have changed dramatically. Looking at emerging trends in artificial intelligence, we can expect more changes in engineering work in the future.

Given this, we believe that the career aspirations of engineers need to change. In particular, rather than aspiring to a job in a well-credentialed firm and trusting their professional development to the organisation, engineers need to treat their career as an innovation project. That is, they need to empower themselves to own their careers. They should have an idea of what “innovation product” they want to become, and should work out the trajectory they need to follow so as to get someone else to pay them each step of the way. They should also be prepared to “pivot” their careers as they learn more about their strengths, weaknesses, opportunities, and aspirations. In order to do that, they need to have the ability to reflect on their work and their behavior, to give constructive feedback to others, and to receive constructive feedback from others.

Summary of changed skill requirements

In summary, in order to thrive as junior engineers, we have identified the following skills graduates need beyond technical design skills:

- Execution of conceptual design
- Team work
- Inter-cultural understanding and empathy
- Conception of their careers as an innovation project
- Self-empowerment in their attitude to their careers
- Ability to reflect critically on their aspirations, strengths and weaknesses in relation to available opportunities
- Ability to give and receive developmental feedback

Responding to changing student needs

At the Melbourne School of Engineering, we have responded to these imperatives by creating a new required subject called Creating Innovative Engineering (CIE). Melbourne Engineers need to complete a Master’s degree to qualify as engineers. We hope that students will use it to frame their education, and to see the various technical skills they acquire as tools in a toolbox designed to create value for clients. In addition to teaching students to see engineering as being about value creation, and not technical problem-solving, we aim to change their mindsets in two other ways. First, we want them to see their careers as innovation projects, and second, we want them to leave the subject having taken ownership of their careers. We do not aim to give them mastery of the various conceptual design and interpersonal skills. Instead, we aim to give students rudimentary skills and a passionate interest in developing them over time.

To achieve this, we solicit innovation challenges from sponsors, inside the university and out. Sample projects can be found in the Appendix. The sponsoring organisation provides an innovation challenge for students to work on, and also provides a mentor who comes into the classroom and works with a team of 5-6 students for the semester. We constrain the sponsors to projects that require the students to go out and engage with users, customers, or other recipients of value from the innovation. We also strongly prefer projects that are intrinsically attractive to engineering students for some reason or other.

The subject is positioned at the start of the Master of Engineering degree and is one of a number of co-elective core courses. Although we would like all students to take the subject, that would require us to solicit 100 projects per semester, instead of the current 30, given current enrolments in the school. It would also require a delivery and logistics capability beyond that of our current organisation.

We equip the students to work on the project in two ways. First, we instruct them in “design thinking” and give them various practical tools to complete the project. Second, we instruct them on things they can do to make their team more effective. To do this, we present the classes in a workshop style with teams seated at tables with their mentor. The classes are three hours long and generally comprise three components. In the first we present innovation-related theory and practices. In the second we apply the same issues to their careers and personal development, while in the third they work on their project.

The semester takes them through a project process built around a “double diamond” human centred design process (Liedtka & Ogilvie, 2011). In the first week we introduce the students to the subject and the projects. In the second we allocate them to teams and they learn about the project and the sponsor from the sponsor. In the third we teach them how to interview, and about cultural difference and empathy. In subsequent weeks they are taken through a process of gathering data, analysing it for insights, generating innovation ideas, constructing value propositions, ensuring those ideas are strategically consonant with the sponsor, and then pitching the idea to the sponsor and the group. We also have a session on pivoting – which is vital both for the projects that run awry and for the “career as innovation project” metaphor.

A thread runs through the semester that talks about changes in the nature of engineering work, and links the innovation project they are working on to the idea of their career as an innovation project. We emphasise that if their careers are innovation projects, it is imperative that they develop skills in reflection and feedback. Consequently, the students write a reflection each week and give feedback to a peer each week.

RESULTS

While the subject is still in the early stages of development, and we do not have quantitative measures of program performance, we have several qualitative indicators of success. The subject is popular with many students, and a significant proportion describe it as the best subject they have taken. Students have started to spontaneously solicit projects from their employers after taking the subject. Many students ask to be involved in the delivery of the subject after they have completed it. Other students, not surprisingly, cling to the idea that engineering = technical problem-solving, and so believe the subject is a poor use of their time. Many of them change their understanding during the semester (i.e. education occurs!). As we get better at delivering the subject, we expect more of them to change their views, and earlier. Sponsors generally choose to return in subsequent semesters and some mentors recommend the experience to their friends and colleagues. Some students have been hired from the subject, and several projects have been developed further for implementation.

The program is expensive and logistically difficult to run. It takes significant effort to recruit sufficient projects, and a lot of effort to sculpt project scopes that meet the needs of both the program and the sponsors, ensure all the legal documents are signed on time by the companies and the students, and that everyone starts the semester with a mindset that will lead to all participants being successful.

CONCLUSIONS

Changes in the nature of engineering mean that students need to develop a mindset that doesn’t equate engineering with technical design, and the skills to work in a world where they need both conceptual design and technical design skills. The inclusion of real-world projects in the classroom leads to high levels of student satisfaction and can give students an appreciation of the challenges in real-world innovation and conceptual engineering design.

APPENDIX: SAMPLE PROJECTS

- Develop the conceptual design for a system using machine learning and computer vision to monitor people to prevent them from injuring themselves. Use a local maker space as a prototypical application location.
- The system that allocates riders to lifts in a major city building induces a large number of complaints, particularly among building users with high accessibility needs. This problem is exacerbated as the tenant moves to hotdesking and activity-based work. The team's task is to work out whether people could be allocated to lifts in a way that better serves both building users and the building owner.
- A leading IT company has new technology that enables it to count people in crowds (on trams, at tram stops, on the street) much more accurately than existing methods. It also has deep capabilities in Artificial Intelligence. It would like to combine these to create an offer that adds significant value to Public Transport in Melbourne. The team's task is to design with such an offer.
- A global leader in the IT space with deep expertise in Artificial Intelligence would like to offer products and services to the financial sector. The team's task is to design a product or service in the broad area of risk management. The product or service must be one that the financial institutions would prefer to purchase from a third-party provider, rather than create it themselves.
- Vertical gardens are promising to be an essential component of future urban environments. The project aims to identify a better way to build and maintain vertical gardens.
- What opportunities does the rise of electric vehicles, and the associated need for battery charging and electricity storage create for a company that has historically provided construction, operation and maintenance services in the power distribution industry?
- Provide an environmentally and financially sustainable solution to manage stormwater sediment in a wetland system while meeting community expectations.
- Has the vehicle seen me? Will it stop? Autonomous vehicles are the future, but how do we as passengers, pedestrians and other drivers gain confidence in them. What systems could be developed to help indicate what the vehicle is thinking?
- Currently, stroke patients get insufficient therapy, because therapists don't have the time to work with them. A research group in the Department of Mechanical Engineering at the University of Melbourne has developed a robot to help provide therapy for stroke patients so that therapists can leverage their time. This project will work on the conceptual design of the user-interface, broadly defined, to make the robot attractive to therapists and patients.
- A leading producer of eggs has a by-product stream of 230 m^3 per week of manure from just one of its farms (on the suburban fringe of Melbourne). How can it maximize the value (financial, social, environmental) from this valuable resource?
- One of the developers of the Docklands precinct must decide how to develop the last parcel of land in its portfolio. The nature of the parcel, its location, and the development plans are such that it could easily create an alienating place. Alternatively, it could be the hub with a vibrant community. The developer would prefer the latter, and invites the project team to help it work out what attributes to incorporate in the development plans.
- A metropolitan water retailer would like to know how to best offer a variety of water options to domestic customers to reduce overall demand on drinking water, provide choice and value to customers, and potentially new revenue streams for the retailer.
- My Victoria is an open data platform aimed at small to medium businesses to help them make informed decisions. Using geospatial technologies, users can over lay demographic information (e.g. population) on to map based information (e.g. public transport), to get a good idea of a suburb. How might this platform be used by Food Trucks when making decisions about where to park day to day?

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