

THE CREATIVE ENGINEERING EDUCATION IMPERATIVE FOR TWENTY-FIRST CENTURY LIVING

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ABSTRACT

Engineering and design in the twentieth century were conventionally taught from opposite ends of an educational spectrum. Engineering education built certainty on a strong foundation of fundamental knowledge, with students engaging with applications only once those fundamentals were ingrained. Design, in contrast, involved challenging certainty, with divergent thinking, experience mapping, problem framing and exploratory research. Over the last twenty years, an element of creativity and design process education has progressed into the majority of engineering curricula, but change is still slow. Yet, meanwhile, the pace of technological change impacting engineering futures and has been rapid. Arguably, the ability to be open and responsive to radical changes in thinking will become increasingly vital for engineering educators and practitioners with the unknowns of rapid change, both technical and social. For future engineering professionals to be able to be responsive to each wave of disruptive technology, engineering educators will have to re-invigorate their efforts in the adoption of pedagogy that supports creativity and innovation in order to keep pace. In addition, engineering graduates need to be educated not only in how to respond creatively to new technologies but in retaining the human-centred focus of development in an environment where rapid technological change has the possibility of fracturing or supporting human centred and community development. This paper proposes a return to education aimed at producing holistic engineers who integrate social aspirations and technological innovation into their work, as in the nineteenth century, to safeguard human development in the digital era of the twenty-first.

Keywords: Disruptive technology, civil, 3D printing, experiential learning, innovation

1 INTRODUCTION

Much as during the first industrial revolution, the disruptive nature of technological change during Industry 4.0 has been keenly felt because of its corresponding impacts on work patterns, consumerism, production systems and business practices, as well as intangibles, such as social attitudes, expectations and behaviours. In his book, *The Future*, Al Gore states that there are “so many revolutionary changes unfolding simultaneously and converging with one another” that they are creating a “clear consensus that the future now emerging will be extremely different from anything we have ever known in the past. It is a difference not of degree but of kind” [1]. The incremental, relatively slow pace of human development of the twentieth century is being challenged by the disruptions and paradigm shifts of digital connectivity and change and this can be a cause for concern. According to Kelly [2], a human’s “ability to invent new things outpaces the rate we can civilize them. These days it takes us a decade after a technology appears to develop a social consensus on what it means”. Whilst this suggestion has implications for all educators, the human aspects of the statement are arguably particularly relevant for engineering academics at this time. This is because as engineering education has evolved over the last century, it has been taken in ways that are diametrically opposed to the radical shifts caused by the global megatrends around digital immersion-based thinking and practise discussed by futurist Hajkowicz [3]. Whereas the global megatrends identified by Hajkowicz relate to connectivity and empathy, the trends governing engineering curriculums worldwide have predominantly taken the discipline further towards a systemization based approach and over the last hundred years have created engineers increasingly narrowly educated who would therefore be ill equipped to deal with the current situation: “First we shape our tools, and then the tools shape us” [4].

In the 2016 book, *Design Engineering Refocused* [5], the role of innovation in engineering in the twenty-first century is discussed. In the chapter *Engineering as Exploration* [6], structural engineer John Ochsendorf criticises the “hyper-specialisation” of contemporary engineers that was also highlighted by the high profile Indian architect and urban planner, Charles Correa in his 2004 essay “In Search of Brunel” referred to by Ochsendorf, and laments that engineering education is failing to respond to the rapid pace of technological change in any meaningful way: “Compared with the staggering pace of change in computing, biomedical engineering or nanotechnology, the field of structural engineering can seem frozen in time” [6]. Ochsendorf argues for the ability to create technologically informed innovation to be taught to students, and places it within a need to return to a more holistic view of engineering, as epitomized in the work of engineers such as Isambard Kingdom Brunel, Gustave Eiffel and Robert Marillart. He describes their engineering innovations as informed by their understanding of engineering in context, allowing them to invent new technological possibilities whilst, significantly, also responding to the social aspirations of their time. He suggests this is in direct contrast to the portrayal of engineering during the last hundred years as “lone genius, achieving beauty through constraints of economy and efficiency” [6], with little concern for the implications of their decision making on the human condition or experience. Belski et al argue that the contraction of expertise in engineering practice has been a necessary response to the “explosion of engineering knowledge-base that forced engineering practitioners to significantly shrink their fields of expertise and to specialise only in very narrow areas of technology” [7]. However, with the advent of disruptive technological change in the twenty-first century causing a radical rethink of what systems thinking means - and what human evolution in a time of digital immersion looks like, engineers such as Ochsendorf are calling for the teaching of engineering disciplines, such as civil engineering, to be rethought, coming full circle so that engineers are again taught to be the foremost creative thinkers in society, tackling the social and environmental problems of their time. To do this, engineering needs to shift from its mathematically dominated curriculum towards a greater mix of subjects that support the development of visionary thinkers who able to respond to the stimulus of rapidly changing technological innovation, whilst steeped in social and environmental engineering and community welfare.

2 DIVERGENT THINKING

As engineering evolved in academia over the last century, it was increasingly broken down into its essential components, with the systemisation of engineering usurping the problem framing and social context implications considerations evident in earlier work. Yet the existence and longevity of conferences, such as the *Engineering and Product Design Education* conference, speak to a desire in engineering education to explore the commonalities between engineering and product design. According to Harford [8], in the book *Messy: How to be creative and resilient in a tidy-minded world*, there is a history of breakthrough scientific research based on divergent thinking, informed by cross-disciplinary practice, rather than as more traditionally portrayed as based on the ‘scientific method’ of research where a predetermined hypothesis is tested to confirmation. He provides examples, such as in the work of leading Hungarian mathematician, Paul Erdos, who deliberately chose to work across problems, and drift between research disciplines in order to inform innovations in his particular field, declaring “My brain is always open!” [8]. Ochsendorf argues in favour of this view and the related imperative of changing engineering teaching towards a divergent research approach: “Engineering education emphasises unique solutions, which can lead to a reluctance to explore. But the greatest engineers are ceaseless explorers“ [6].

In recent years, leading engineering institutions (e.g. Olin College) have worked to reset engineering education by providing experiential learning over didactic learning in the first year of an undergraduate degree. The aim has been not only to improve the retention of information – and students – through student centred learning but also to provide a means for students to engage in more exploration through open ended problem solving. Whereas design practice and education is conventionally led by divergent thinking at the start of a project, engineering education has traditionally focussed on the building blocks of foundational knowledge leading to validated outcomes for problem solving, based on conventional wisdom and knowledge. For many engineering academics, the shifts to open-ended problem solving and experiential learning are challenging in themselves and have led to the development of systematic creativity strategies (e.g. Howard et al 2007 [9]). The focus for the reasons given for this shift so far have predominantly been around improved

deep learning of the established fundamental knowledge base and improvements in the retention of students between first and second year. However, there has not yet been a notable shift in discussion on educational pedagogy to developing students who can genuinely respond to the era of disruptive technological and social change they are living in. The focus for student learning in order that they can respond to the true spirit of Correa's lament, needs to be on understanding engineering in context and subsequently, developing informed problem framing and divergent thinking strategies based on research, not just a reworking of problem solving and creative thinking activities.

3 OPEN ENDED PROBLEMS

"Instead of providing a unique solution for the design team to accept or reject, the best engineers can map the design constraints in a productive way" [6]. At Griffith University in Australia, a new course was introduced in 2014 called Creative Engineering to address these challenges. Initially offered as an elective to third and fourth year engineers alongside first year industrial design students, this course is now a core first year course to all the engineering disciplines on both campuses of the university (2017). The course aims to introduce engineering first year students to problem framing, divergent thinking, iterative design process, convergent practices, evaluation and discussion informed by the work of innovative engineers. However, the underlying message presented to the students through this course is a view of engineering fundamentals as embedded within the framework of their operational context, rather than apart from it, and the difficulties of working with uncertainty: "Engineers must become creative and innovative as they contend with uncertainty, complexity, and constraints in unfamiliar cultural settings. They must also deal with a multitude of technical and nontechnical issues beyond their accustomed practice" [10]. Whilst Amadei is referring to engineers working overseas on sustainability projects, the underlying sentiment provides a good basis for approaching the evolution of engineering education to respond to current technological and social disruptions. At Griffith University, learning in the Creative Engineering course was based on an exploration of risk and uncertainty and the human complication factor. The learning assessments built progressively to take the students through increasingly independent learning experiences, with open-ended scenarios.

The actual project areas can change each year, but the key to making the course work was the focus on informed process, not product. Students were acknowledged for learning and reflection that is characterised by stepping back to consider the larger context for their work, then focussing in to a specific problem area they identify within the project, and repeating the process throughout the project. By the final assessment, students were asked to identify their own project area, one with a human element as well as a technical one, and to map the project area extensively before beginning, then creating their own brief. Students were encouraged to choose a project area to study that they could identify with, which resulted in students addressing problem areas as diverse as the problem of people ignoring flooded road warning signs; elephants causing disruption in a village on the edge of a reservation and supporting emotional and physical needs of mother and baby in the transition from breastfeeding to bottle feeding. The common requirement in the projects was that they started from a user-centred starting point. Students need to research not only the functional needs of the target market but the cultural referencing and behaviours, the social norms and attitudes of that group: "Culture is what is distinctive about the way of life of a people, community, nation, or social group" [11].

Their work needed to identify and respond to the human aspects of the project, showing evidence of the student exploring the social norms that may be specific to that group, and how that understanding informed their work. Although this is accepted practice in design disciplines, the integration of empathy into engineering programs in more unusual and faces additional challenges because of the majority culture in engineering that has developed over the last hundred years. The research work of Baron-Cohen [12] provides the basis for an argument that engineering student cohorts and academic teams are typically dominated by systemisers, who are at the opposite end of the emotional spectrum to empathisers. Therefore the proposal to shift learning in engineering programs towards empathy-based project work creates more extensive challenges to the discipline than might appear on the surface. Loy et al [13] argue that specific - and innovative - professional development will be needed to support engineering departments in changing attitudes and embracing this shift.

4 CIVIL ENGINEERING INDUSTRY 4.0

“Nowadays, companies are demanding a type of civil engineer that is not the one created by our current education systems and there are several surveys which confirm this fact Roberston 2002; Russell and Stouffer 2005; Bernold 2005. Students are required to have certain skills, such as communication, teamwork, innovative thinking, critical thinking, creativity, design capability, which are not developed with the traditional education systems. Many recent graduates are incapable of formulating creative solutions to problems they have never seen before; therefore, they do not have the ability to solve “real world messy problems” and open-ended problems” [14].

Considering the most challenging area of engineering in the context of this paper, researchers Aparicio et al [14] report that civil engineers have been reduced over the last hundred years to “structural analysts”. They argue that civil engineering education needs to be overhauled in order to meet the needs of current employers and provide graduates who are capable of contributing more effectively to teams working on complex problems. Their work provides examples of educational projects that extend the student beyond a predominantly analytical role into consideration of the design of the structure as a whole, with analysis subsequent to that initial starting point. Whilst this is a step in the right direction in order to meet the required graduate attributes they identify, it arguably still falls short of providing the depth of learning experience necessary for students to attain those graduate attributes. This is because it is based on expanding the role of the civil engineer within the existing profile of projects in construction that dominated during the twentieth century. In the twenty-first century, civil engineers, like everyone else, are being impacted by the rapid expansion of disruptive technologies. For civil engineers to be educated for future employers, educators need to project student-learning aims forward to anticipate the learning needs of students affected by Industry 4.0.

Civil engineering is a structured discipline, with a comprehensive body of knowledge on which practicing engineers can call on to provide solutions of incremental change for individual situations. Of all the engineering disciplines, civil is arguably the least directly impacted by disruptive technology, yet the reality is that this group just as much as for any other engineering discipline will need creative engineering. However, even civil is not immune to the impacts of technological innovation characterised in Industry 4.0, and the necessity they bring for educators and practitioners alike to reconsider the boundaries of the profession and the learning required to work within in. Take, for example, surveying large tracts of inhospitable land. From the introduction of vehicle mounted long range scanners, to the more recent introduction of long distance drones capable of supporting air-based landscape mapping, the nature of information being provided by these changing technologies is different. It will become necessary for students to understand these technologies sufficiently to relevantly collect and apply the data. Other crossover digital technologies for civil engineering include virtual reality, augmented reality and - more recently - mixed reality as a means to map and discuss a project prior to its development. An extreme example of this has been the use of such technologies by NASA when considering the development of structures on Mars.

For civil engineering education, this is not purely about adding technological capabilities, but rather recognising that digital technologies and disruptive innovation create change, and change will require graduates to be open and responsive to new ideas and new ways of tackling projects. In educational terms, the impact is on challenging students to explore beyond traditional boundaries, not for the content specific learning they gain, but for the ability they will develop to continue that exploration after graduation, and look outside conventional discipline wisdom for creative answers to emerging problems. This approach not only improves their divergent thinking in practical terms, but also introduces them to people and projects outside their normal scope. Cross-pollination and the tendency to work on multiple projects simultaneously, described by researchers Gruber and Davis as a ‘network of enterprises’ [8] has been found to be common practice amongst creative people.

Essentially, actively addressing the integration and maximising of new technologies as they emerge requires engineers, including civil engineers, to have a more creative mindset. There are good examples in civil that demonstrate this ability, such as illustrated in the work of Heijmans in the Netherlands, in collaboration with TU Delft and Intron in developing what they have called ‘Self-Healing Asphalt’. This result came from a new and creative way of looking at the problem of replacing asphalt. The life expectancy of noise-reducing topcoat asphalt is around eight years. Removing and replacing the asphalt releases CO₂ as well as causing significant disruption to traffic and considerable costs. Heijman’s self-healing asphalt is laced with fine metal fibres. An induction device can then be driven over the asphalt, generating heat and melting the surrounding asphalt. This

causes hairline cracks to close up, and regenerates the adhesion in the asphalt, thus extending the life of the product.

Heijmans are embracing innovation, and are leaders in the development of 3D printing applications for civil engineering projects. Again, they are working collaboratively with organisations from different disciplines, such as MX3D in exploring the potential of 3D printing to build bridges.

For educators in this field, looking beyond the conventional examples to emerging practices in non-traditional sectors such as 3D printing, and integrating these into student projects would push students – and academics - into creative thinking practices simply because there is no pre-existing reference material to rely on. The work on innovators such as Digital Grottesque and Dus Architects demonstrate that accepted ideas on wall structures, both for aesthetic and functional reasons, need to be revised. The ability to 3D print large-scale sand moulds, as demonstrated by Bruil in the Netherlands, opens up new areas of research, structural engineering and design. The use of topologically optimised 3D printed building connectors by Arup impacts the design of construction product and its use, allowing for further innovation.

In addition to changing physical properties to structures, the study of 3D printing in civil engineering allows educators to bring in the social and economic implications of disruptive technologies. For example, the Quake column designed by Emerging Objects provides students with an opportunity to rethink the design of earthquake tolerant structures, but also it introduces the idea of 3D print ‘Build Farms’, and distributed manufacturing. The implications for civil engineering education of a rethink of manufacturing and production systems in the context of design for sustainability take students out of traditional learning spaces, and encourage divergent thinking and research.

The other major digital disruption to impact the development of structures in radically innovative ways is connectivity. Just as the Internet of Things is radically changing Product Design, the ability to collect and analyse data in real time throughout a structure is changing ideas on the way buildings are used. MIT demonstrates this in their work on responsive environments. For civil engineering educators, working on the functional and social implications of the integration of sensors in buildings takes them into cross-disciplinary teams outside their usual sphere. Civil engineering education in the twenty-first century should look very different to that of the last century.

5 HUMAN EVOLUTION

This is not about innovation solely for commercial reasons. Rapid changes enabled by digital technologies, such as in relation to data generation, collection and analysis, will impact the development of the human psyche. Gore argues that digital immersion from an early age will shape the evolution of human behaviours and relationships over this century [1]. The pace and extent of technological change happening at this time inevitably will have impacts on human development that cannot currently be anticipated. Yet the work of engineers maximizing technological opportunities going forward will also have impacts on individuals and communities, as well as the environment and global economies. Engineers need to be educated to at the very least be cautious of these impacts and understand the context they are working in: “Could the people who began the Industrial Revolution foresee the ecological effects and loss of life caused by the rise of factory systems, chemical manufacturing, machine tools, coal burning, and mining?” [15]. If the pace of technological change continues exponentially post the digital revolution, then engineers need to ensure the work is grounded in the human experience. To do this, students should be encouraged to work on human centred problems, before focusing in on specifics. In this, the direction of engineering education will be aligned with the changes in direction experienced in design over the last twenty years, and further collaborations across the disciplines should be encouraged.

6 CONCLUSION

The ability to be open and responsive in the face of radical changes in technology and ideas will become an imperative for graduates in preparing for effective working practices. The engineering profession needs to be educated not only in how to use new technologies at a faster pace, but also in understanding engineering in context. Engineering over the last hundred years has become divided into hyper specialisations. Yet engineers in history have pioneered social change with designs that are embedded in a deep understanding of context and the impact of their work on human development. Whilst learning the fundamentals in engineering is essential for the rigorous development of validated solutions, the engineering profession is not immune to the megatrends that are impacting. As

technological change provides the potential to radical revise production systems, work patterns, consumerism and more, it is vital to teach students to be engineers who can consider challenges holistically, and respond creatively to the opportunities and challenges presented. Retaining the human-centred focus for development in an environment where rapid technological change has the possibility of fracturing or supporting human centred and community development. Engineering education cannot afford to evolve at its current pace to integrate elements of creative thinking and design process into the curriculum, but rather it needs to be radically overhauled to create students confident of tackling complex problems that involve the human experience.

To do this, students need to be introduced to values based education in the first year of their studies, exploring strategies for evaluating and supporting human development in the digital era of the twenty-first century. Engineering in context, human challenges, designing for living and empathy rather than systemizing bring engineering closer to design disciplines, and it is that link that will help the academics to shift the culture and take education forward to produce genuinely twenty-first century engineers that can stand alongside Brunel and his contemporaries in providing creative, innovative, holistic responses for complex problem solving. Holistic solutions and human-centred creativity are arguably a particular challenge in engineering over other disciplines as it has a recognized educational culture that currently favours systemization over empathy. Yet it needs too happen, because as technology becomes more complex, and the very nature of problems change with current paradigm shifts, there will be a lack of reference material for the graduates of the future to be able to turn to. Innovative thinking and engineering in context needs not only to be possible for these graduates, but a requirement, in order that society can have engineers who can navigate the changing landscape, and provide informed, human solutions as well as technical ones.

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