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The Distinctiveness of Civil Engineering in Engineering Systems Thinking and in New Models in Engineering Education

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Word count: 4,709

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A revolution in engineering education is coming, but is civil engineering ready? Students learn differently from how they did a few generations ago and the rapid pace of technology change means that the goals of education need to change as well as the method. New engineering degree programmes are arising, and though they aspire to teach a new generation of interdisciplinary engineers, they do not seem to have been developed with civil engineers in mind. While the need for improvements in systems thinking by engineering students is acknowledged by various organisations, the uniqueness of a civil engineering response to the systems challenge is not recognised. Civil engineering education is distinct because of the large scale of the artefacts that need to be created by students, because the scope of civil engineering employment is broader, and because its need in terms of systems thinking is more than project management. The conclusions are that (1) civil engineering education needs rapid and major change, (2) a unique focus on systems is needed in civil engineering education, and (3) civil engineering education needs to follow a distinctive path from the forms that the revolution is currently taking.

Keywords: systems; engineering education; new models in engineering education; Olin College; Constructionarium

# 1. The Need for Change

Roughly ten years ago, the call for major engineering education reform echoed around the world through a set of major reports:

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| --- | --- | --- |
| Country | Title | Organisation (reference) |
| U.K. | Sustainability and the Formation of the Civil Engineer | Institution of Civil Engineers (Jowitt 2004) |
| U.S.A. | Educating the Engineer of 2020: Adapting Engineering Education to the New Century | National Academy of Engineering (2005) |
| U.K. | Educating Engineers for the 21st Century | Royal Academy of Engineering (2007a) |
| Australia | Engineers for the Future: Addressing the Supply and Quality of Australian Engineering Graduates for the 21st Century | Australian Council of Engineering Deans (King 2008) |

The reports made similar points about the need for change in education to reflect recent and expected changes in engineering practice. The key needs noted were for:

* graduates who are better able to handle the complexity of interdisciplinary problems
* education that involves more team-/group-work
* more innovation and adaptability by graduates
* closer ties to engineering practice during study to anchor other learning.

Following on from these efforts have been other important analyses, including some focused particularly on civil engineering (Galloway 2007). The most influential effort has been the 2014 book by Goldberg and Somerville, *A Whole New Engineer: The Coming Revolution in Engineering Education*. They write that the missing basics in engineering education are: (1) questioning, (2) labelling, (3) modelling, (4) decomposing, (5) experimenting, (6) creating, and (7) communicating. A formative gathering on the topic of holistic engineering led to a book of the same title with papers by participants. In that work, Grasso and Heible (2010) say that the student educational experience will need to change to stress innovation and creativity in design and will be personalised, multidisciplinary, liberal, systems-oriented, integrated, and interactive. The need for change has, if anything, become greater since the national-level reports from 2004–2008. Goldberg and Somerville quote Thomas Friedman: ‘Increasingly the world does not care what you know. Everything is on Google. The world only cares, and will only pay for, what you can do with what you know.’

Although some incremental change has occurred within curricula, the most significant change has been the introduction of new educational institutions redesigned around new models of education. The new engineering programmes at Olin College and the New Model in Technology and Engineering (NMiTE), because of their small size and newness, might not be believed to be much of a threat yet to the standard educational model, but the strong contrast to other engineering schools has already highlighted how great a change in education might be needed to meet the new challenges. These new programmes have a greater emphasis on hands-on experiences, case study analysis, and design teams. If it becomes clearer that they are more successful than standard programmes, there could be a rapid push for further change in the next ten years.

One way that the new programmes are succeeding is by attracting good students. Too few high school students study the required maths and sciences to allow for engineering study, and too few appreciate the challenges and joys of an engineering career. Providing more or better information to students and parents is not enough. In addition to issues associated with socio-economic conditions and the health of the home environment, there is the issue of adjusting education to match the motivations of today’s students. A detailed examination of the motivations of students entering the University of Illinois found three primary career interests of potential engineering students (Goldberg and Somerville 2014):

* Technology entrepreneurship
* Social entrepreneurship/activism
* Cool technology

The education of today’s students needs to better match how they learn. Today’s potential students have come through a very different pre-university system than their instructors experienced, and they have been taught to learn by working on projects, often in small groups, with less learned through lectures, readings, and fixed lessons.

Goldberg and Somerville quote Tony Wagner: ‘The programs that do the best job of educating young innovators focus on intrinsic motivation for learning through a combination of play, passion, and purpose.’ Intrinsic motivation (rather than extrinsic motivation in the form of commands to learn certain material in a certain way) in turn is fostered by giving students more autonomy (power to control their education), purpose (working on projects that matter to them), and mastery (students self-evaluating to show that they have mastered concepts, and so taking pride in their learning). Many of these ideas are not new to civil engineering (Elms 1992). A new engineering education model built around hands-on experiences, case study analysis, and design teams will better attract the students we want to attract and better match their learning styles.

The need for change is strong. How strong? Again quoting Goldberg and Somerville, ‘… the culture of engineering education is fundamentally misaligned with the times, … [and] major culture change—not minor shifts to content, curriculum, and pedagogy—is necessary.’ The general form of the change needed might also be clear, but the details much less so. How to tailor these general engineering education trends to civil engineering education in particular?

The need for change is recognised to include a need for engineering education to improve its teaching of problem solving, integration, interdisciplinarity, socio-technical analyses, and systems thinking. However, tailoring these improvements to a civil engineering degree, in particular, has been less well examined.

This paper examines these issues by looking in more detail at the new engineering education initiatives to highlight that they have not been developed with civil engineers in mind. It then explores how the cloth of systems thinking in engineering education has been cut in ways that are less than well-fitting to civil engineering education. After examining whether civil engineering’s distinctiveness is missing, the focus turns to considering how well suited environmental and chemical engineering education will be to the current directions lauded for the engineering education revolution. The paper closes with a call for us (with or without other related disciplines) to develop a clearer articulation of what the coming revolution means for the civil engineering community.

# 2. New Initiatives

Although the case for radical change is strong and the vision is clear, the actual movement in engineering education has been modest. NMiTE in the U.K. is looking to accept its first intake of 300 in the autumn of 2019. It intends a new form of education with an emphasis on creativity, design, innovation, technology–society interactions, and passion. All of this is very much a radical, rather than incremental, response to the call for change.

The site in Hereford will be a different type of campus, without lecture halls or large classrooms, but instead with studios, worklabs, workshops, and seminar rooms. Adjoining the campus, and sharing facilities, would be an innovation centre for small, start-up businesses. Students would find education and engineering practice interlinking on many levels throughout their education.

The topics to be covered (not within a standard lecture-based curriculum, but still indicative of the areas of emphasis for design and innovation) are indicated as:

* mathematics
* mechanics
* thermofluids
* measurement
* electronics/circuits
* engineering materials
* signal processing
* energy systems/conversion, and
* computing.

NMiTE looks to Olin College in the U.S.A. as one of its models. Olin had its first graduating class in 2006, and has by multiple assessments provided a high quality and highly sought-after, while distinctly different, engineering graduate. Its curriculum model emphasises superb engineering, entrepreneurial thinking, creativity, design, and examinations of social impacts. There are also hands-on design projects every year, and a high level of student engagement in the whole of the educational experience. Again, this is all a clear response to the call for change.

Looking more closely, all students at Olin learn about software, electronics, and mechanical systems, and they can receive a degree in either mechanical engineering or electrical and computer engineering. They can also create a degree with a concentration, and popular areas of concentration are bioengineering, computing, and robotics.

Other programmes, either new or more established, have also responded to the call for change. Like NMiTE and Olin, they focus on mechanical, electrical, and software engineering. The response in civil, chemical, and environmental engineering appears to be very modest. For study in these areas, Aalborg University in Denmark seems to have a programme closest to the Olin–NMiTE model. Aalborg offers engineering degrees in civil and structural engineering, water and environment engineering, and chemical engineering and biotechnology, all within a case-study-rich engineering education. The curricula have operated since the 1970s and today have roughly half of the credits from team projects and half from more topic-focused courses. The projects are real-world-based, with the social impact of technology increasing in importance as students progress through the degrees. There is a high interaction with practising engineers, the laboratory experiences are good, and the university has sophisticated methods for assessing students in team projects. This emphasis on problem-based learning develops some of the calls for change, but not all of them.

# 3. The Acceptance of Systems Thinking

There seems to be broad acceptance that part of the change needed in engineering education is a greater emphasis on systems thinking. The links between systems thinking and multidisciplinarity, social–technical analysis, problem-based learning, and design are strong; for example, ‘There is a need to embed multidisciplinary approaches based on systems thinking, with strong industry links, within all engineering courses’ (Royal Academy of Engineering 2007a). Improved focus on systems thinking in engineering education is expected to improve learning of:

* integrated design
* analysis of interdisciplinary problems
* analysis of social/technical interactions
* analysis of complexity
* management of risk and uncertainty.

Similarly, as of February 2017 the INCOSEUK website explains that ‘Systems thinking is a way of thinking used to address complex and uncertain real-world problems. It recognises that the world is a set of highly interlinked technical and social entities that are hierarchically organised producing emergent behaviour.’

Just as the overall need for change in engineering education is strong but the actual execution to date is weak and not very relevant to civil engineering, one might say the same for systems thinking: there has been much more talk than action, and the action that has taken place seems of less relevance to civil engineering education. Wise (2010), from Lockheed Martin, seems to consider systems engineering as a mix of product development and project management.

Systems engineering … includes some basic core steps … :

* Analyse the customer requirements
* Plan the technical effort
* Define potential candidate solutions and conduct trade studies
* Optimise and evaluate alternatives
* Design
* Verify/validate that requirements are met

Closer to my part of the world, the University of Auckland requires all engineering students to take ‘systems’ courses in managing a project and managing a business. They focus on case-study learning and incorporate several important parts of the need for change, such as forming interdisciplinary engineering teams, and considering technical, social, and enterprise issues jointly. Hearteningly, the University of Auckland seems convinced of the benefit of more systems thinking in education. Unfortunately, their courses focus mostly on engineering project management, and operate with very large teams of up to 17 students, limiting the ability of students to see the whole, and without focus on other aspects of systems thinking.

The Royal Academy of Engineering (U.K.) paper *Creating Systems that Work: Principles of Engineering Systems for the 21st Century* (2007b) seems to follow a similar path, with a focus on improving engineers’ ability to design integrated systems, while overlooking much of the other important aspects desired through an upgrade in ‘systems thinking’.

Austin et al. (2010) point a way forward:

Systems engineering is often treated as though it were a combination or derivative of other engineering fields, or not true engineering at all, but a topic in management. The way to move beyond this problem is to describe the practice of systems engineering as being the foundation for ‘technical leadership’.

A recognition of the need for technical leadership should lead naturally to a better understanding of systems dynamics (Senge 2006), and to the application of systems thinking in engineering education when studying social and economic systems (Godfrey, Agarwal, and Dias 2010).

# 4. Applicability to Civil Engineering

There’s a need for change, but change is coming slowly to civil engineering education. There is a need for improved systems thinking in engineering education, but civil engineering needs are not being met well. It seems that a significant problem that has not been recognised is that civil engineering education is different from education for mechanical, electrical, software, and aerospace engineering. Perhaps the case for change and the responses to those calls for change have, to date, focused on the latter group with the assumption that something very similar could be done for civil engineering education. If that assumption is not true, it would not mean that there is no need for change in civil engineering education, or that none of the new efforts are relevant, but it would mean that a civil-specific response is needed to the challenges of engineering education and systems thinking.

The Royal Academy of Engineering report (2007a) highlights the values of the CDIO initiative for engineering education, in which students learn engineering fundamentals in the context of **C**onceiving–**D**esigning–**I**mplementing–**O**perating through group experiences in workshops/laboratories that include, for example, building small planes and rockets. Many first-year engineering design courses around the world take a similar approach, often with an explicit emphasis on the process of design more than the content learned.

Although the CDIO initiative is meant to apply to all engineering disciplines, the limitations of a similar approach for civil engineering are great. A project involving just conceiving–designing–constructing is challenging once beyond the most basic civil engineering artefacts (e.g., spaghetti bridges). Physical scale is important in civil engineering, and to effectively simulate a real-world experience requires something larger than a university seminar room or standard laboratory. A large space, adequate materials, and appropriate safety protocols and specialised equipment all matter. The U.K. Constructionarium project is a wonderful experience for teaching students the three steps and helping them see CDI in a real-world context. The challenges in developing that new programme and maintaining it are substantial, both logistically and financially. The challenges of extending the one Constructionarium experience to another where, say, half of the student time is spent on a series of similar projects over 3–4 years seems vastly greater than a similar effort would be in an Olin College or NMiTE context.

There are also challenges of scope. There is scope in terms of life-cycle for real-world civil engineering projects. The issue of sustainability and life-cycle analysis for civil engineering projects is more challenging than for some other engineering disciplines; consider the deconstruction and long-term restoration associated with dams. Setting aside the knottier cases, there are plenty of more common ways that today’s civil engineering needs to consider the ‘operate’ aspect of a CDIO project. How can we have teams of eight students do a realistic CDIO contract for a toll bridge? There is also a scope challenge in terms of the less integral nature of many civil engineering projects. Increasingly, civil infrastructure projects are not for one specific item, such as a building, and are more for a complex or a network, such as the maintenance of a set of roads for a municipality. These reasons make it more challenging to create real-world experiences for civil engineering students in a campus-setting.

Finally, there are the differences of civil engineering organisations to consider. While NMiTE might foster connections between start-up companies and students in a campus when the projects relate to mechatronics or new software, it is hard to imagine something similar for civil engineering students. There would be great benefit in having civil engineering students interact more with small groups of practitioners and imbibe some entrepreneurial spirit from that experience, but in a campus setting it is not realistic to see that happen more than at the margins. Additionally, the desire for entrepreneurship in civil engineering is different: the focus is not to produce graduates who will create their own small companies, come up with new patents, etc.; the focus is on having new engineers who are creative in a team fashion and who can add value to an endeavour through technical adaptability.

Maybe it would help to recognise that civil engineering systems are different from mechanical/electrical/software systems. They are strongly spatial, and therefore more constrained in terms of their links. They are highly capital-intensive. They are more about functions than products. They require large ongoing investments. They are expected to function for very long durations. Another way that civil engineering is different is that the interdisciplinarity needed is not just between engineering disciplines, but also with other professionals—architects, landscape ecologists, sociologists. That implies that interdisciplinary projects for civil engineers would benefit from adding in non-engineering students at least as much as they would benefit from adding in students from other engineering disciplines.

Considering these differences between civil engineering systems and mechanical/electrical/software/aeronautical engineering systems helps explain why systems thinking in civil engineering education needs to mean something more than just integrated design or project management involving multiple engineering disciplines.

# 5. Applicability to Environmental and Chemical Engineering

An analysis of how civil engineering education should differ from that for mechanical/software/electronic/aeronautical engineering runs the risk of ignoring other engineering degrees. To the extent that it makes sense to divide engineering education into two degree clusters, to which cluster should we put degrees such as environmental and chemical engineering?

For environmental engineering, the need for education on issues associated with product development seems remote. The work of environmental engineers tends to be less project-oriented than for civil engineers, and involves a great deal of work in environmental impact assessments and monitoring programmes. Environmental engineering projects became closely tied to biological systems and are very often tied to social systems as well. Academic preparation for environmental engineers would need systems engineering concepts to help analyse these biological and social links. Design and teamwork experiences would also need strong links in those directions.

Consider a societal issue such as river management, one for which society will increasingly need technical expertise. Environmental engineers would need to understand hydrology, waste treatment, contaminant transport, economic valuation, cultural impacts, habitat restoration, effects assessment, decision and risk analysis methods, and so on. Student teams cannot have their own river to modify in the laboratory. They could conduct a case study design project, but even then they might not be able to talk directly to the people affected or measure seasonal (not to mention long-term) effects of different strategies. Trying to directly apply the Olin–NMiTE model to environmental engineering seems even more problematic than for civil engineering. On the other hand, a civil-tailored approach to the engineering education revolution is likely to fit well for environmental engineers too.

Chemical engineering is more oriented towards discrete projects than environmental engineering is, say, with the design of a new component or process for a factory. Scale issues, however, would seem to arise when trying to educate chemical engineering students on many real-world components and particularly on whole processing facilities. I could imagine that chemical engineering education, to be responsive to the call for change, would need to expand to consider improving education of engineers not just on new components, but also on their redesign because of new demands (say, to reduce water use or chemical hazards). Chemical engineering has had a strong past interest in systems engineering that is more akin to the interest found in civil engineering than to how it is now developing in, say, software engineering. Chemical engineering might be more nearly in between the two education degree clusters, with many education issues more like those for civil/environmental engineers, while a few more, such as larger enterprises, are associated with mechanical and electrical engineering.

Engineering education on advanced materials manufacturing and power engineering, for example, would also not fit neatly in the mould of an Olin College because of challenges with the scale of the created artefacts and the size of the relevant engineering organisation. Then there are hybrid degrees (say, for forest engineering or agricultural engineering) that have components of both civil and mechanical engineering. The notion of trying to simplify engineering education by having a neat split into two camps needing distinctly different education modes is fanciful.

Jowitt (2004) explores in detail the teaching of sustainability to civil engineers, but some of the advice would seem very relevant to a wide variety of new broader models of engineering education:

Learning needs to be

* Amenable to the use of case studies
* Studio based
* Issue driven
* Process based
* Team based
* Design/delivery focused

However, it does not follow that there would be no benefit in making it clear that at least two responses should exist to the call for change.

# 6. A Distinct Path?

I assert that a distinct response to the call for change is needed for civil engineering education. The need for change is too strong and the currently accepted models for change do not suit civil engineering well. What should a new model of civil engineering education look like?

If we follow closely the call for change it would be intensely hands-on with educationally vital real-world experiences. In an ideal world, we could imagine such an educational experience with more personal tuition, and more student-centred learning spaces. This ideal-world education would likely cost two to five times more than current education models. I guess I can assume that the cost of change is the underlying reason why civil engineering education seems to lag, and that instead of large changes we are seeing a small set of incremental changes. When the current system at many institutions does not reward engineering educators for bold new efforts in education, it is no surprise that the response to the call for change can lead to a set of relatively small incremental changes. I would assert that this path of incremental change is not enough and that something that is more radical but that does not blow out the costs is needed.

What can be done to get past the impasse? Maybe we could make more use of simulations to have students, as individuals and teams, better prepare for real-world engineering decision-making and civil engineering systems concepts. The highly successful MERIT program (<https://meritgame.com/>) is a good example in the field of construction management of what can be done.

The various reports on engineering education reform mentioned at the start all comment on the need for closer ties to engineering practice throughout education, with a strong desire for work placements. Perhaps the education revolution for civil engineering will need a stronger and longer period of work placement as part of the degree. A recent report in New Zealand (Naylor 2016) reached the same conclusion, but also noted that work placements are not enough when assessments needed for degree completion cannot demonstrate that students are learning adequately from their placements. If more emphasis were placed on the educational value of work placements, with preparatory workshops, ongoing communication during work, and summary reflections afterwards, perhaps the educational value of these experiences would increase. Additional work placement would have to have enough auditable educational value to decrease the need for today’s standard courses or else it would not replace existing teaching but supplement it, thereby increasing the cost to society for engineering education.

The call for change appears to imply a need to change not just what is taught and how engineering is taught, but also to change how students learn and change how we assess competence. Students who need to improve their understanding of social–technical relationships, and to improve their creativity and teamwork skills, also need better personal reflection skills. Assessment as well would seem to need to adapt to a new education model, with more use of oral examinations, multiple assessment of fundamental technical concepts, and consideration of student attitudes and values (Lynch et al. 2009).

Civil engineering serves too critical a role within society for us to continue with modes of education poorly designed for society’s new needs and students’ new ways of learning. I do not believe that incremental change is enough. I am not convinced that we can adapt the new models that exist for education of other engineers without wholesale reconsideration. We can find a different mode of change and set our own path, and perhaps ally closely with other degrees. Our new path must consider the unique nature of civil engineering work and also the unique needs in civil engineering systems education.

Every new journey must begin with a first step. I hope you will consider starting down a new path.

**Acknowledgments**

The author is grateful for the thorough and kind copy-editing of Janet Bray.

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