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Educating Engineers in the 21st Century: The New-Model Engineer

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12th June 2023

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June 2023

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Abstract

Civil engineering has transformed the health, wealth and wellbeing of societies over the past 200 years, however, it is also driving the global climate and environmental crises. The paper identifies that the traditional paradigm of engineering higher education leads to "bounded rationality", which in turn leads to unstable and undesirable system outcomes.

The paper defines a "New-Model Engineer", able to move beyond the behaviours of bounded rationality. Threshold knowledge of engineering fundamentals and outstanding connective skills, embedded within the behaviours of holistic systems thinking, empower the "New-Model Engineer" to be a responsible part of a stable socio-ecological system.

The paper identifies key characteristics of this new education, including: defining appropriate learning outcomes across all three domains of learning; increasing the diversity of students and teaching staff; removal of closed book exams; prioritising threshold knowledge; exposing the limitations of mathematical and theoretical models; developing reflective practice; and adopting experience-led approaches to teaching and learning.

This approach marks a zeitgeist change in engineering education, which the authors believe represents the most exciting opportunity in engineering education for two centuries.

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June 2023

Educating Engineers in the 21st Century: The New-Model Engineer

1. <u>Why</u> we need to reconsider civil engineering education

1.1. Context – a potted history of civil engineering

The profession of civil engineering emerged from the industrial revolution, and has been instrumental in transforming the wealth, health, and life expectancy of societies. The development of specialist disciplines gave engineers the power to achieve Thomas Treadgold's often repeated vision of harnessing the forces of nature for the benefit of mankind (Treadgold, 1828). The huge advances in life-altering infrastructure throughout the 19th and 20th centuries are testimony to the phenomenal success of the engineering professions.

The United Nations Sustainable Development Goals (UNSDGs), shown at Figure 1, were developed at the turn of the 21st century to provide a blueprint for global prosperity (United Nations, 2023). Goals such as Clean Water and Sanitation (6), Decent Work and Economic Growth (8), and Industry, Innovation and Infrastructure (9) align exactly with the priorities of Victorian society, and civil engineering is fundamental to their achievement.

Figure 1: The 17 United Nations Sustainability Goals

However, we are now acutely aware that our current engineering practices are greatly exceeding the carrying capacity of the planet. Referring to the UNSDGs it is striking that civil engineering has a very negative impact on the global, environmental and longer-term goals (such as 12 – 15), which were not seen as priorities when the profession was developed. We are therefore in the paradoxical situation that the institutions and behaviours which we invented to achieve some of these goals, now pose an existential threat to humanity by undermining others. Simply put, civil engineering was invented to solve one set of problems, but we now face other problems too.

Figure 2 is a schematic illustration of human greenhouse gas (GHG) emissions since the industrial revolution. As explained by the authors *"The plot demonstrates graphically the enormous difference in outlook that was required by civil/structural engineers to take society up the slope, and that which is now required to take us down the slope. Bluntly, the outlooks are incomparable."* (Ibell, 2022). Our paradigm for the education, and employment, of civil engineers was developed for the “upslope”, but a radically different paradigm is required to meet the challenge of the “downslope”.

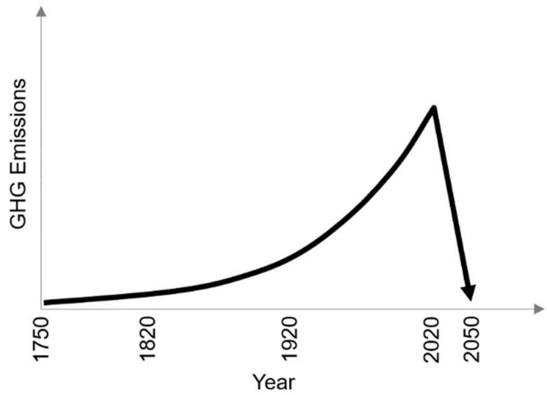


Figure 2: Schematic illustration of anthropogenic GHG emissions since the industrial revolution. Highlighting the "upslope" of increasing consumption, and the required "downslope" of the near future. (Ibell, 2022)

If we are to propose a new paradigm for educating Civil Engineers in the 21st century, it is first important to understand why and how our current paradigm developed, by considering the role of engineers within our wider economic and social system.

1.2. The current paradigm of civil engineering education

The enlightenment and scientific revolution of the 18th century ushered in logic and rationality as the key tools for discovery and decision making. The scientific method used evidence to solve technical problem after technical problem and the industrial revolution put these new discoveries to practical use. New scientific disciplines were created, allowing the emergence of experts in specific fields, and defining the engineering professions and institutions we recognise today. Adapting Adam Smith's famous metaphor (Smith, 1759), economics acts as an "invisible hand" assembling all the discrete specialist elements within the wider socio-economic system, allocating resources, and defining the overall jigsaw puzzle of how the components interact. For this system to work, and therefore transform the wealth and wellbeing of nations, each element (engineer) must fulfil two distinct functions:

1. <u>Expert</u>: Be expert and effective at conducting its discrete specialist task.
2. <u>Commercial</u>: Respond to market forces, such that it can be integrated into complicated project teams and work with other specialist elements.

Our system of higher education is built around developing the first of these points, with individual academics embodying very deep specialist knowledge in discrete fields, and academic modules teaching students how to solve specialist technical problems. Our institutions and professional ethics help ensure the second point, creating engineers who judiciously serve the needs of their paying clients.

The climate and biodiversity crises, the democratisation of knowledge, AI, and innumerable other factors, now make it clear that graduates in the 2020s will require different knowledge, skills and behaviours to those embedded within our traditional engineering curriculums. In the UK, the Professional, Statutory and Regulatory Bodies (PSRBs) are committed to positioning the Climate Emergency central to educational culture for new engineers. The fourth edition of the Engineering Council's Accreditation of Higher Education Programmes (AHEP4) (The Engineering Council, 2020), and the guidance from professional institutions, are unambiguous in the need for urgent change. However, our system of engineering higher education has been constructed to meet the needs of the old paradigm.

1.3. The case for systemic change in civil engineering

1.3.1. Observing the outcome of a system

According to the Sustainability Institute, a *system* is an interconnected set of elements coherently organised in a way that achieves something. A *system* therefore must consist of three parts: *elements, interconnections,* and a *purpose.* (Meadows, 2008)

The important mental leap when assessing systems, is to understand that the *observed purpose* is the observed output from the myriad *elements* and *interconnections.* The stated or desired purpose of a system is irrelevant if the observed purpose or *consequence* is something else.

1.3.2. Identifying the outcomes of the current system of civil engineering

The stated purpose of civil engineering, which emerged from the industrial revolution, was to harness the forces of nature for the benefit of mankind (Treadgold, 1828). As the professions grew, the *elements* and *interconnections* evolved and became well established: Universities started producing engineers with particular expertise (*elements*), and supply chains started producing standardised materials (*elements*); laws, contracts, design codes and institutions formalised the way that these elements behaved and interacted (*interconnections*); and the ethical basis for all of this work was enshrined through institutions (*desired purpose*).

Figure 3 shows a schematic of the current system, whereby engineers continue to transform and health, wealth and prosperity of societies. However, the consequence *(observed purpose)* of these systems also now includes consumption of natural habitats and resources at unsustainable rates, and generation of 11% of global greenhouse gas emission (rising to 39% when including emissions from the infrastructure constructed) (World Green Building Council, 2019). Such unintended consequences are known by economists as “externalities”.

Injuries and fatalities were traditionally a severe negative externality of the UK construction industry, however, the introduction of the Health and Safety at Work Act (HM Government, 1974) placed responsibility for workplace accidents on decision makers. This legislation turned construction safety from an externality into an internality, and thereby ushered in rapid improvement. There is not yet any equivalent legislation for the longer term social and environmental impacts of civil engineering projects, so these threats remain as externalities. Left unchecked, the current system of civil engineering is optimised to respond to commercial drivers, and will therefore continue on the catastrophic “upslope” as shown in Figure 2.

2. <u>What</u> we need to change

2.1. Increasing connectivity and feedback

In a famous thought experiment, Garrett Hardin described the tragedy of the commons, explaining how groups of individuals, making isolated rational decisions, are incapable of effectively managing a shared resource and will inevitably lead to the decimation of the resource, to the collective detriment of the entire group (Hardin, 1968):

Hardin’s theory can be interpreted to imply that destruction of common resources is inevitable without some form of externally imposed rules or regulation. Research by Elinor Ostrom shows that some human systems are able to self-organise, self-regulate and self-heal (Ostrom, 1999), rather like ecosystems. These human systems are able to overcome the pitfalls of blinkered self-interest when individual behaviour is influenced by myriad different feedback loops. Greater connectivity between elements overcomes the barriers which would otherwise lead to destructive behaviours, ultimately leading to the protection of the vital common resource.

Inventing boundaries between ever more specialised engineering disciplines has been vital to advancing scientific knowledge and has unlocked the ability for our economic system to combine the elements into ever more powerful and complex project teams. However, these boundaries are now the exact thing which inhibits feedback between different disciplines, thereby allowing the *observed purpose* of our industrial system to morph out of control. Nobel Prize-winning economist Herbert Simon coined the term Bounded Rationality, to describe the situation where people make rational decisions based on the information they have available, but are unaware of the wider consequences, or “externalities” (Simon, 1955). Engineers working to solve technical problems, where decisions are dominated by discrete commercial or technical metrics, are a clear example of bounded rationality in practice.

2.2. Countering bounded rationality

No engineers want to cause social or environmental damage, but a system which inherently "bounds rationality", and limits engineering decisions to a narrow band of metrics, inevitably leads to unstable system outcomes.

This foray into history and theory demonstrates that:

- The invented boundaries between different scientific and engineering disciplines have provided engineers with huge power to convert natural resources into economic and social outcomes;
- These same boundaries have simultaneously removed the feedback loops which prevent inadvertent negative system outcomes;
- The current economic and industrial system (of which civil engineering is a major part) has exceeded the carrying capacity of the planet and is now posing an existential threat to humanity;
- Appropriate feedback between elements is vital to avoid the dangers of bounded rationality, and keep any systems stable.

Figure 3 depicts the current paradigm, with engineers as bounded technical specialists, contributing to an unstable system. Figure 4 depicts engineers as a source of connection and feedback, contributing to a stable and resilient system.

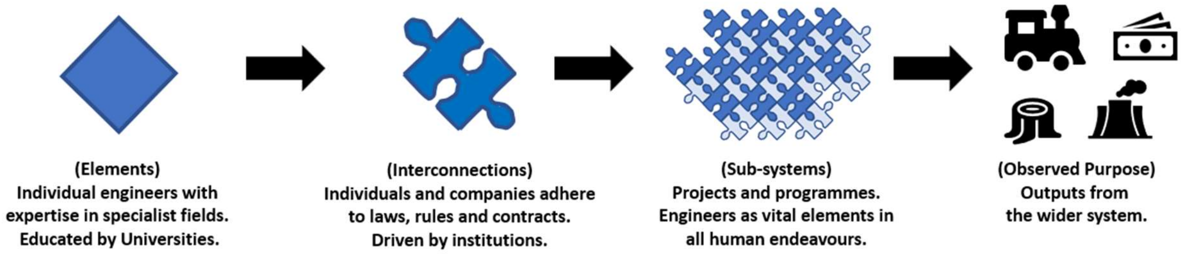


Figure 3: The current paradigm; engineers as "bounded rational" elements in a powerful, but unstable, wider economic system

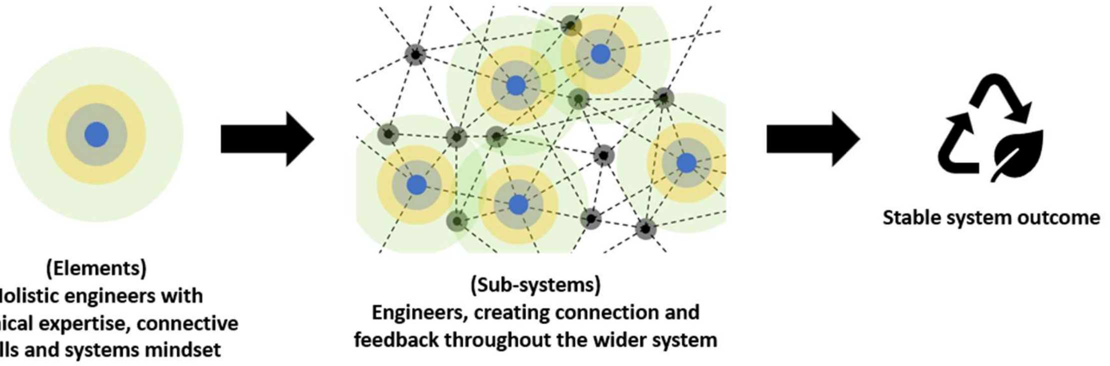


Figure 4: The required paradigm; engineers generating myriad sources of feedback, as part of a stable system

2.3. Increasing resilience

The current paradigm of engineering (Figure 3) is excellent for delivering large and complicated projects, however, it is inherently vulnerable. The individual elements (i.e. engineers or companies) have limited ability to adapt, and the interconnection between the elements is vulnerable to economic or social upheaval. The lack of connection between distant elements undermines the ability of the system to rapidly reorganise, meaning that it is inherently slow to adapt in the face of change.

By contrast, in the new paradigm (Figure 4) engineers have a broader range of threshold technical skills, which allows them to make rapid and sound technical decisions, even in new situations. The improved connective skills allow these engineers to recognise and respond to change, and then rapidly reorganise as part of a resilient system.

2.4. The New-Model Engineer

Technical expertise and knowledge remain the bedrock of being a professional engineer, and distinguish the engineer from other professions. Figure 5 represents the current paradigm of engineering education, with a major focus on the technological advancements which have so benefited humanity. The supporting ethical and commercial behaviours are added, enabling engineers to function as part of wider commercial project teams.

However, the lack of feedback and interconnections with wider social and ecological systems have allowed our human-natural system to become dangerously unstable; with civil and structural engineers driving climate change and biodiversity loss. Achieving feedback and interconnections requires more than just technical knowledge; decisions must incorporate externalities, and engineers must be influenced by, and have influence on, myriad other human and non-human elements in the wider system. The challenge for engineering education, therefore, is to create engineers who still embody specialist engineering expertise, but without the artificial boundaries which lead to unstable system outcomes. Figure 6 represents a new paradigm for engineering education, which complements deep technical expertise with the affective skills and wider mindset which unlock feedback throughout the wider system.

 **Old-Model Engineer**

	• Specialist technical expertise
	• Moral and ethical basis • Commercial behaviours

Figure 5: Old-Model Engineer; the current paradigm of engineering education for the "upslope"

 **New-Model Engineer**

	• Specialist technical expertise
	• Threshold technical ability
	• Connective skills; communication, creativity, collaboration
	• Holistic / Systems thinking • Seeking and creating feedback throughout the system • Appreciation of externalities, such as longer term environmental and social consequences

Figure 6 : New-Model Engineer; the required paradigm of engineering eduction for the "downslope"

Improved connective skills and holistic thinking will be the hallmarks of the New-Model Engineer. Improved education will go some way to improving these outcomes, however, another key element will be increasing the diversity of the students we recruit, thereby bringing a wider range of skills and perspectives with them into the profession.

2.5. Alignment with the UN Sustainable Development Goals

Considering the UNSDGs we can compare the likely behaviours and actions of an Old Model Engineer to those of a New-Model Engineer. Figure 7 depicts UNSDGs, schematically indicating how a civil engineer may be expected to impact, positively or negatively, against each of the 17 goals. It can be seen that the Old Model Engineer might be expected to prioritise economic growth and short-term local societal benefits, generally represented by the lower numbered SDGs at the top of the list. However, the holistic thinking and greater connectivity of the New-Model Engineer allows them to also prioritise global, environmental and longer-term impacts, generally represented by the SDGs at the bottom of the list. The New-Model Engineer is therefore able to achieve a greater balance across all 17 of the UNSDGs, and critically, is able to avoid having the negative impacts indicative of the Old Model Engineer.

Sustainability implies a degree of stability and could align with the notion of 'doing no harm' against the UNSDGs. However, given the enormity of the biodiversity and climate crises there is now increasing awareness of the need to change from a sustainability mindset to one of being regenerative, whereby the actions of engineers actively improve social and environmental outcomes. The New-Model Engineer depicted in Figure 7 is therefore shown as acting somewhat regeneratively, where their actions have a net-positive impact on UNSDGs such as Responsible Consumption (12), Climate Action (13), Life Below Water (14) and Life on Land (15).

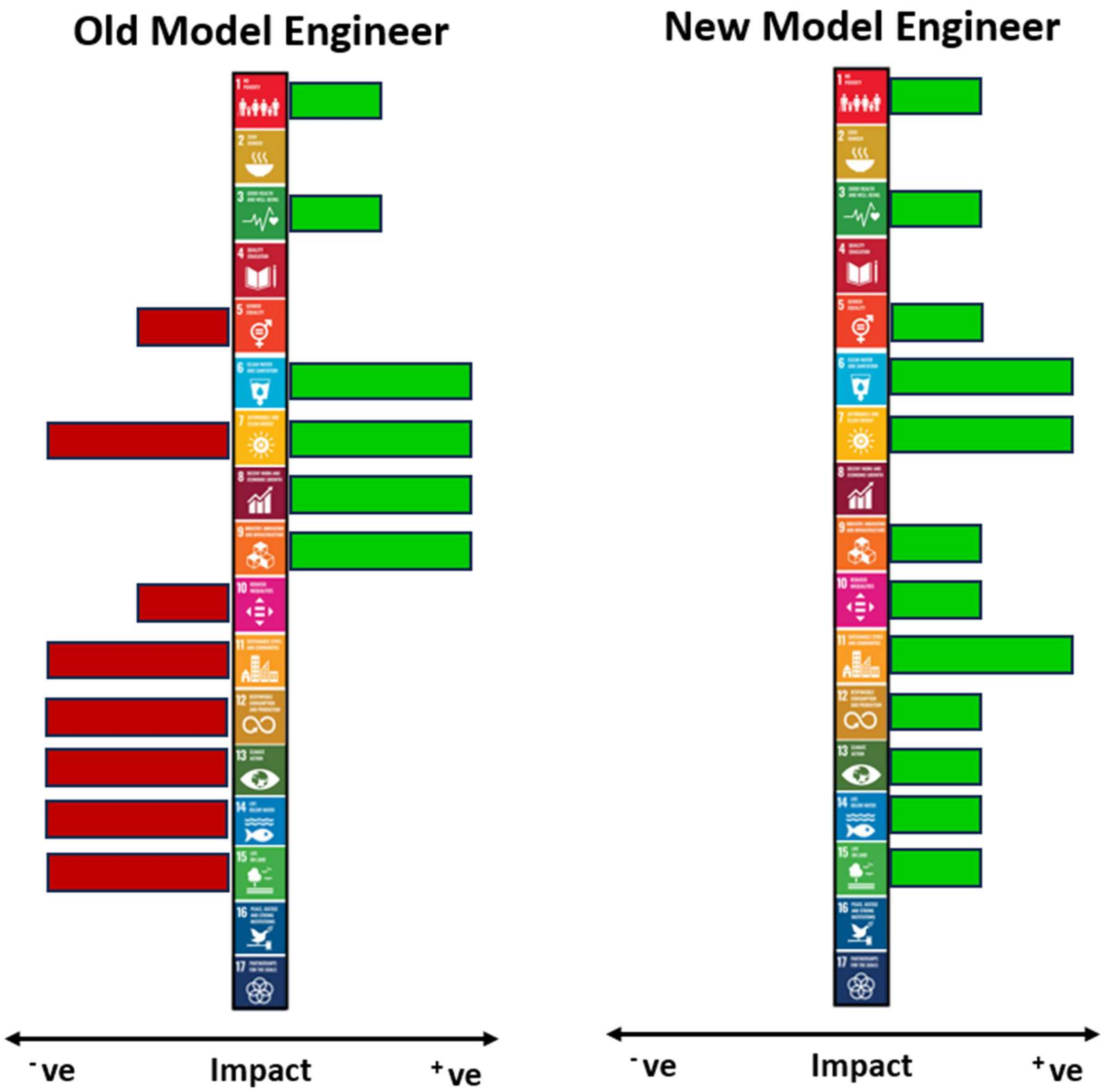


Figure 7: Schematic illustration of possible impacts of an Old Model Engineer versus a New Model Engineer, judged against likely contributions to the 17 UN Sustainable Development Goals.

2.6. Pedagogical considerations for the New-Model Engineer

Educational theory identifies that there are three different domains of learning, as shown in Figure 8 (Krathwohl, Bloom, & Masia, 1964). Each of these domains has a hierarchy of learning outcomes, and students can move up through the hierarchy as they master a topic, as shown in Figure 13 (Krathwohl D. , 2002).

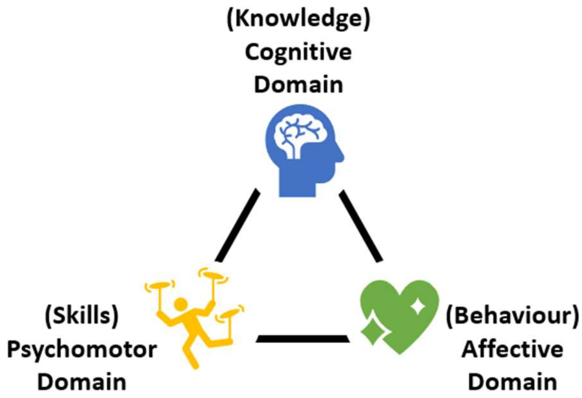


Figure 8: Three domains of learning: Knowledge, Skills and Behaviour

Engineering degrees inevitably span all three of these domains, however, they have traditionally been dominated by the knowledge domain. It is customary for all learning outcomes to be defined in terms of the knowledge domain, and assessments strongly reinforce this perception by prioritising knowledge over wider skills and behaviour. A schematic illustration of the typical balance between learning domains for traditional engineering higher education is in Figure 1Figure 9. This focus on obtaining new knowledge aligns with the paradigm of the 'Old-Model Engineer', as shown in Figure 5.

By contrast, the 'New-Model Engineer' should have a balance of learning across all three domains, as indicated in Figure 10. Learning outcomes must be defined in terms of the skills and behaviour domains, as well as the knowledge domain, and assessments must truly value and reward all three domains.

Figure 9: Schematic illustration of a typical balance between learning domains for the traditional education of an "Old-Model Engineer"

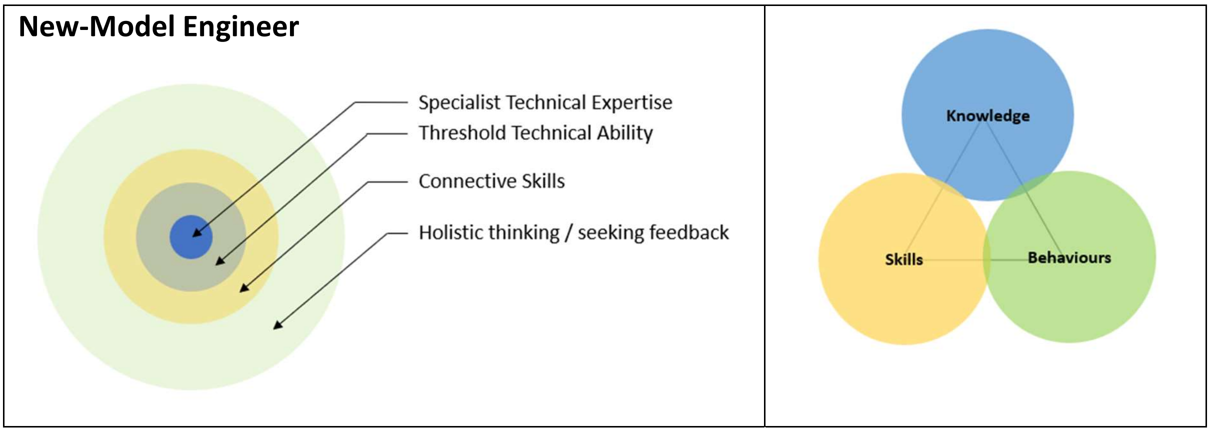


Figure 10: Schematic illustration of the proposed balance between learning domains for the "New-Model Engineer"

This rebalancing between the learning domains implies a reduction in technical knowledge, which is, of course, anathema to many engineers. However, this apparent loss may not be as problematic as it appears, for four reasons:

- **Methods of Learning**. The improved teaching of skills and behaviours can be achieved <u>whilst</u> acquiring new knowledge. There is, therefore, no inevitable sacrificing of knowledge in order to improve teaching in the skills and behaviour domains.
- **The changing nature of knowledge**. Our access to knowledge is now completely different to what it was 200, 50 and even 2 years ago. Internet, smart phones and AI have transformed our ability to immediately access information. Time spent on retention and recall of facts could therefore be better used.
- **Specialist technical expertise**. The New-Model Engineer will continue to develop very deep technical expertise, but only in the later years of an undergraduate degree and post graduate studies, and possibly in narrower fields.
- **Threshold technical abilities**. The New-Model Engineer should have a robust understanding of key engineering principles, and be able to apply these in a practical context.

3. <u>How</u> this change can be implemented

Transitioning from the education of Old-Model Engineers to the education of New-Model Engineers, represents a fundamental shift in engineering higher education. At the highest level we must first challenge our overall "system" of education, we must then ensure that we are achieving appropriate diversity in everything we do. We can then identify appropriate learning outcomes and educational methods, suited to teaching and learning for New-Model Engineers.

3.1. Change the system (check what's on the bookcase)

Regenerative design uses the analogy of a bookcase to help understand our systems (Broadbent & Norman, 2023), the books on the shelves represent the characteristics of how we educate engineers, and the shelves represent our hierarchy of concepts (Figure 11):

- The top of the bookcase is the 'paradigm'. These are the rarely opened, big heavy dusty books, which define the mental framework into which we slot everything else.
- The next shelf down is for 'mindsets'. These are the goals, values, and theories on which all actions and decisions are based.
- The third shelf down is for 'rules'. These are the operations and regulations that define what we do.
- The bottom shelf is for 'habits'. These are the precedents and automatic responses that help us make quick day-to day decisions.

A key characteristic of the systems bookshelf is that a book can only go on a shelf, if it is in line with the principles of the books on the shelf above. Therefore, the day-to-day habits on the bottom shelf only stick if they align with the rules on the shelf above, and the rules only work if they align with the mindsets defined on the shelf above them. In turn, the mindsets only stick if they are aligned with the top-shelf paradigm, therefore, changes to the system require opening and questioning the heavy books at the top.

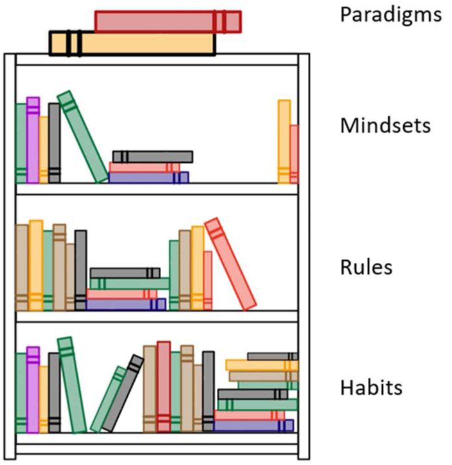


Figure 11: The systems bookcase.

In changing to educating the New-Model Engineer it will, of course, be vital to change many of the 'habits', with the introduction of carbon calculations, repurposing existing buildings, and lower impact materials being obvious examples. However, if the rules, mindsets, and paradigms on the shelf above are still aligned to the Old-Model, the system will still continue to educate Old-Model Engineers, just with subtly different knowledge.

The challenge for educators is therefore threefold: Firstly, to recognise the heavy books on the top of the shelves which lock engineering education into the old paradigm; secondly, to change the books on all the shelves so that they align with the needs of the 21st century; and thirdly, to educate students to be aware of the bookcase, so that they can adapt and choose their own books in an uncertain future.

3.2. Seek diversity

3.2.1. Diversity of staff

In the development of technical solutions, engineers must also consider all the outputs of the system including the environmental impact, the financial implications and ethical and societal considerations. The educational model should, therefore, develop the skills and attributes required to take a holistic vision and address the problem from multiple angles and the academics delivering the model must also have diversity of skills, experience and expertise.

It is clear from the Joint Board of Moderators' guidelines (Joint Board of Moderators, 2023) and The Engineering Council's Accreditation of Higher Education Programmes, AHEP4, (The Engineering Council, 2020) that the Professional, Statutory and Regulatory Bodies (PSRBs) are committed to positioning the Climate Emergency central to educational culture, and the New-Model Engineer is very much in line with the guidance. However, without radical change, learning outcomes such as "Evaluate the environmental and societal impact of solutions to complex problems and minimise adverse impacts" cannot be achieved with current curricular structures. The word "complex" features sixteen times in the AHEP4 learning outcomes and is defined by the JBM as "…engineering problems, artefacts or systems that involve dealing simultaneously with a sizeable number of factors that interact and require deep understanding, including knowledge at the forefront of the discipline, to analyse or deal with". This emphasis on complexity and the holistic nature of engineering projects creates a tension within schools of civil engineering which tend to be divided into subject specific silos to which academics are generally recruited and valued for their research. Academics can lack experience in the connective skills and systems thinking which characterise the New-Model Engineer. Civil engineering departments must therefore educate their current staff, and recruit new staff, to increase expertise in the affective (behaviour) domain of learning.

3.2.2. Diversity of students

Complex problems require complex teams to address them. Engineers should be a diverse group of people who will approach problems from many angles and who have a variety of skills, strengths and attitudes to tackle the complex systems challenges inherent in the 21st century.

One of the main selection criteria for applicants to civil engineering degrees is their mathematical ability, generally implemented by A Level maths as an entry requirement. This creates a barrier for the majority of university applicants and greatly reduces the diversity, in terms of the abilities and strengths of civil engineering students. Excellent mathematical skills are essential for a small number of highly technical engineers, but an excessive focus on mathematics systemically undervalues the wider adaptive and connective skills which are essential to the New-Model Engineer.

3.2.3. Diversity of thought

Increased diversity doesn't just apply to the academics and students but must also apply to thought as engineering moves away from the bounded rationality paradigm.

An initial approach to broaden diversity of thought may be to routinely consider all decisions from three different perspectives: social; ecological; and time. Kate Raworth's work highlights the importance of balancing ecological and social needs at both the local and global levels, defining these as "four lenses" (Doughnut Economics Action Lab, 2022). The impact of civil engineering projects can be felt over centuries and even millennia, therefore, the practice of civil engineering should also consider time.

Figure 12 illustrates the "four lenses", mapped against the time perspectives relevant for civil engineering. The shading provides a schematic illustration of where thought and effort are usually focussed in the current paradigm of civil engineering. However, it can be seen that catastrophic global externalities, such as climate breakdown and longer-term social wellbeing, are largely excluded by the bounded rationality of the current paradigm.

As well as aiming for a balance between the three learning domains, the education of the New-Model Engineer should also aim to achieve a balance across all the perspectives shown in Figure 12.

Figure 12: The 'four lenses' which should be considered in civil engineering projects. The heat map schematically illustrates the relative time and importance typically dedicated to each factor in current industry and education.

3.3. Educating the New-Model Engineers

3.3.1. Define appropriate learning outcomes

As indicated in Figure 10, education of the New-Model Engineer will require a balance of learning across the three domains of Knowledge, Skills, and Behaviours. Educators must, therefore, avoid the pitfall of defaulting to Knowledge based learning outcomes and teaching methods, for those topics which should actually sit in the Skills or Behaviour domain. Figure 13 lists the three different domains of learning, and identifies the different levels of learning, from basic at the bottom to advanced at the top of each list. Against each level of learning are appropriate words to describe learning outcomes. The learning outcomes for education of the New-Model Engineer should therefore draw on a balance of all these words. Methods of learning in the knowledge domain are very well established in higher education, but learning in the other two domains requires significantly different approaches.

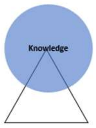
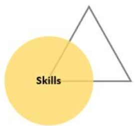
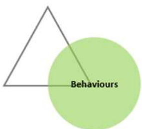
Domain of Learning	Level of Learning	Examples of learning outcomes
(Knowledge) Cognitive	Creating	Assemble, Construct, Create, Compose, Develop, Formulate, Invent, Originate, Write
	Evaluating	Appraise, Argue, Decide, Critique, Criticise, Defend, Judge, Prioritise, Rate, Select, Support, Value, Evaluate
	Analysing	Categorize, Compare, Contrast, Deduce, Discriminate, Distinguish, Examine, Question, Separate, Test
	Applying	Apply, Change, Choose, Construct, Demonstrate, Dramatize, Employ, Illustrate, Interpret, Modify, Operate, Produce, Schedule, Sketch, Solve, Translate, Use, Write
	Understanding	Classify, Describe, Discuss, Explain, Identify, Locate, Recognise, Report, Select, Translate, Paraphrase, Visualise
	Remembering	Define, Duplicate, Draw, List, Label, Memorise, Name, Recall, Recite, Repeat, Reproduce, State
(Skills) Psychomotor	Natural (highly proficient)	Automatically, Effortlessly, Naturally, Professionally, Routinely, Spontaneously, Easily, Perfectly
	Articulate (coordinate related acts)	Confidently, Coordinate, Harmoniously, Integrate, Proportion, Smoothly, Quickly, Reliably
	Precise	Accurately, Effortlessly, Independently, Proficiently, In Control
	Manipulate (follow instructions)	Follow, Repeat, Make
	Imitate (follow a demonstration)	Align, Follow, Grasp, Repeat, Try
(Behaviours) Affective	Internalising, such that values control behaviour	Justify, Influence, Modify, Propose, Qualify, Question, Revise, Solve, Apply, Verify, Challenge, Act, Discern
	Organising, building a consistent value system	Adhere, Alter, Arrange, Combine, Compare, Complete, Defend, Explain, Generalize, Identify, Integrate, Modify, Order, Organize, Relate, Synthesize, Prioritise, Recommend, Formulate
	Valuing the worth of information	Demonstrate, Describe, Differentiate, Explain, Follow, Form, Initiate, Invite, Join, Justify, Propose, Select, Share
	Responding and actively learning	Answer, Assist, Comply, Conform, Discuss, Help, Label, Perform, Practice, Present, Read, Recite, Report, Select, Tell, Write, Explain, Study
	Receiving and paying attention	Ask, Choose, Describe, Follow, Give, Hold, Identify, Locate, Name, Point to, Select, Reply, Use, Observe

Figure 13: Learning outcomes, at different levels, across three domains learning

3.3.2. Maintaining specialist technical expertise

The transition to the New-Model Engineer sees a new emphasis on connective skills and holistic systems thinking. However, New-Model Engineers will continue to become the leading academics and technical design consultants of the future so specialist technical knowledge will always be at the heart of engineering higher education.

The key difference in the education of New-Model Engineers is that this deep technical expertise must always be in addition to threshold technical abilities and connective skills, and always in the context of wider holistic, systems thinking. New-Model Engineers will still need to solve tightly defined technical problems, however, this must not be the default for worked examples and exams, but rather an occasional and deliberate decision to solve a problem in isolation, before then re-emerging to consider the wider system impacts.

3.3.3. Developing threshold technical ability

Society holds civil engineers in high esteem, expecting them to make safe and reliable decisions. The PSRBs ensure that curriculums cover an appropriate range of topics, however, it is still possible for engineering graduates to obtain a high-level degree whilst having significant holes in their basic understanding of some topics. This deep specialism works well for the current paradigm of civil engineering, however, it can lock engineers into narrow specialisms and thereby further reinforces the problems of bounded rationality.

These threshold engineering competences will define the flexible and robust professionals, trusted by society to respond in a volatile and uncertain future. This breadth of knowledge should be at least as wide as currently taught, but at a basic level.

Threshold testing, by contrast with academic exams, ensures a basic level of competence across key areas. The New-Model Engineer should be expected to reach this lower threshold across all the key disciplines of civil engineering, in order that they can competently tackle diverse emerging challenges, innovate safely, and be part of a robust and stable system.

Our system of engineering education should therefore incorporate teaching, learning and assessment of threshold competencies. Students should be expected to score near full marks in these assessments, and may be permitted to repeat several times until the required level is attained.

Threshold testing should not be considered a replacement for academic grading or ranking of performance, but should, instead, be viewed as the threshold competence required to become an engineering graduate, akin to passing a driving test.

3.3.4. Teaching connective skills

The New-Model Engineer will require connective skills such as communication, collaboration, creativity, and critical analysis. Using the teaching of surgeons as a framework for the way engineers can learn in the skills domain, the first step prepares and familiarises students with the task and identifies their existing skill level. Next, students develop a conceptual model of the skill, practice it themselves and then be given specific and timely feedback with the opportunity to reflect. Mastery of the skill is then achieved by repeating this process many times (American College of Surgeons, 2020). The New-Model Engineer is not developing psychomotor skills in the same way that a surgeon might, but it is clear that this type of approach to learning would be excellent for topics such as delivering presentations, engaging in challenging discussions, or generating concept designs. Assessment of skills is often subjective (such as feedback on presentations), but clear marking criteria and structured feedback, and regular repetition, can make this assessment as transparent and objective as possible.

3.3.5. Nurturing holistic systems thinking

Nurturing New-Model Engineers to have a holistic and systems thinking perspective is sits in the behaviour (affective) domain of learning. Project-based approaches to learning, and a greater emphasis on personal experiences and reflection, offer appropriate methods for teaching in the behaviour domain.

For some time, experience-led learning has been recognised as an excellent way of developing the holistic skills and attitudes required of modern engineers (Broadbent & McCann, 2016), and project-based learning (PjBL) is widely recognised as attracting a more diverse range of people (Fidler, 2021). PjBL requires students to take a holistic approach to the engineering project, and environmental, ethical, social and financial aspects become as important as the technical. PjBL prioritises the development of communication and team-work, allows students to work on complex problems and to make mistakes in a safe environment. Questioning, challenging and reflection is encouraged and assessed. Assessments can be professionally relevant and assess a wide range of skills.

Many Universities embrace reflective practice as a key method of learning, however, within engineering departments it is often considered of secondary importance to results in bounded mathematical examinations. Gibbs' Reflective Cycle (Figure 14) is just one of many commonly used reflective templates, however, it is illustrative in the way that it breaks reflection into a very rigorous process, which can be learned and practiced as a discrete academic skill. In the early part of engineering higher education the priority should be on learning how to reflect, with particular emphasis on recognising emotional responses (step 2) and then placing the experience in a wider context and relating it to other theories (step 4). Reflection should then be practiced, through repetition and feedback.

One of the hugely powerful benefits of learning to reflect is that it makes New-Model Engineers highly versatile and robust. Even if they are facing completely new challenges, or they lack specific technical knowledge, the ability to reflect and learn will be a key skill in an uncertain future, equipping engineers to rapidly adapt as part of a resilient system.

1. Describe an experience: Factual summary, what exactly happened?

2. Identify your emotional response: How did it make you feel?

3. Evaluate the experience: What went well? What went badly? Why?

4. Analyse the experience: What was the wider context? How did this compare to previous experiences? What other examples or literature can help you to understand what happened?

5. Draw conclusions: What were the alternatives? What have you learned?

6. Action plan: How will you improve? What will you do differently next time?

Figure 14: Gibbs' Reflective Learning Cycle (Gibbs, 1988) with explanatory notes.

3.3.6. Rewarding the appropriate knowledge, skills and behaviours

Unfortunately, the traditional approach doesn't just omit some key learning, it can actually make things worse, by inadvertently embedding inappropriate attitudes and behaviours. Research by another Nobel Prize-winning economist, Daniel Kahneman, shows that the cognitive bias of priming gives disproportionate importance to the first things people learn, as this forms their unconscious world-view, which influences all subsequent decisions and behaviours (Kahneman, 2011). Educators are therefore in a uniquely powerful position to influence the behaviour of generations of engineers. Repeatedly teaching with case studies and exercises based on new buildings can embed a life-long bias towards demolition and new construction; prioritising the teaching of steel and concrete embeds a feeling of comfort, and therefore preference for these materials over less damaging alternatives; and teaching of mathematical techniques without context undermines engineers' connection with the natural and social world.

Methods of assessment are one of the most powerful ways of shaping students' attitudes and behaviour. Closed book exams directly assess knowledge assimilation and recall, and the ability to quickly solve tightly bounded problems in complete isolation. Rather than promoting connective skills and holistic thinking, closed book exams actively devalue these behaviours.

The principles of constructive alignment (Biggs, 2003) identify that everything students do, through their formal curriculum, informal activities, and rewarded through assessments, should align with the desired learning outcomes. Tightly bounded technical problems should always be considered in their wider real-world context, and precise mathematical solutions should not be conflated with the idea that complex problems have simple right/wrong solutions. Engineers must, of course, continue to be assessed in their ability to solve discrete engineering problems, but a large part of all assessment must also reward demonstration of connectivity and holistic thinking, and the ability to reflect and adapt.

4. Conclusion

The authors believe that we are entering the most exciting period to be a civil engineer for over 200 years. Today's graduates will spend their careers working on the "downslope", stabilising our natural environment, and applying technical expertise to supporting humanity through crises. Universities have a responsibility to prepare these graduates with the knowledge, skills and behaviours which will enable them to become capable and adaptable elements in a new socio-ecological system.

The New-Model Engineer will remain the bastions of deep technical expertise, but they will also have the broad threshold technical abilities needed to quickly adapt and innovate in a crisis. They will have outstanding connective skills, to generate and respond to feedback, and will have the holistic systems mindset needed to offer clarity and leadership in the face of fundamental systemic change.

Educators now bear the awesome responsibility of leading this transition from the Old-Model Engineer to the New-Model Engineer. This change not only calls for updating educational content, but more importantly, increasing diversity of the recipients and transforming the approach to teaching. By aligning the learning experience with the connective skills and holistic behaviours required in the 21st century we can empower a new generation of engineers, to help humanity flourish on a thriving planet.

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