LITERATURE REVIEW

Engineering Rebellion Literature Review

This literature review forms the background material for ICE's Engineering Rebellion steering group round-table debate, which aims to develop an impassioned and visionary narrative on the civil engineer of the future and the steps ICE must take to ensure that the profession will be ready.

The following nine areas need to be addressed and are referred to as 'problem statements' affecting civil engineering currently, inhibiting it from achieving the needs of the future. These challenges, addressed in each section, are:

- **Business models**
- **Profile of construction workers**
- **Digital**
- **Sustainability**
- **Productivity**
- **Foresighting methods**
- **Systems thinking**
- **Diversity**
- **Engineers embracing upskilling**

Hyperlinks to sources are provided in the text where available.

1 BUSINESS MODELS

The starting point for understanding the effect business models will have on the future civil engineer can be summarised by Susskind and Susskind (2015) in their book, The Future of the Professions: How Technology Will Transform the Work of Human Experts. They provide a comprehensive analysis of the economic mechanisms affecting knowledge – which they argue is the main commodity of the professions – that are subject to significant change because of the sophistication of the digital technologies that are now being developed. Two-thirds of the book is devoted to this topic, which includes models of how professional tasks and the business models of the professions are likely to have to evolve as a result of these economic processes.

Many recent influential reports have also argued that civil engineering and the infrastructure sector more widely must adopt different business models to survive. These will be described in section 1.2.

1.1 Detailed technology and economic focus according to Susskind and Susskind (2015)

The Susskinds' argument rests on two parts: the evidence of the transformative rate of change and especially the nature of that change, in digital technologies; and an analysis of knowledge as an economic entity that helps to explain the way 'the professions' use knowledge, and hence the significance of digital technology.

Susskind and Susskind's overall argument is that, as a result of the dramatically increasing capabilities of digital technologies, combined with customers' inability or reluctance to continue to pay high prices for professional services, some professional tasks are being performed better (as good quality or better quality; and cheaper) by others outside professional services firms. Previously professional tasks are now being done by para-professionals, freelance labour, outsourced labour in developing economies, and digital technologies.

This trend will intensify over time, with increasing reliability, efficiency and reduced cost from new task methods, especially from digital technologies. This leaves professionals and para-professionals, whether within or outside professional services firms, with a reduced, and reducing, portfolio of tasks from which to obtain income.

While Susskind and Susskind see opportunities for professionals to adapt to these changes in the short and medium term (in the next two or three decades), and provide models for assessing the likely viability of new professional tasks for this time period, they are highly doubtful about the continued existence of 'the professions' many decades hence.
This is a striking conclusion, but is the logical outcome of their analysis of the increasing sophistication of digital machines, and their economic analysis. These will be described in the next two sections: the third section will summarise the implications of these two lines of argument, and how the professions should respond.

1.1.1 Increasingly sophisticated machines

The Susskinds agree with many other commentators that it is a cliché for a new technology to be accompanied by predictions of 'radical change' that are wildly exaggerated (e.g. Brynjolfsson & McAfee 2014; McKinsey 2018). However, like Brynjolfsson and McAfee and others, they argue that digital technologies will bring radical change to human society for four reasons:

- Exponential increase in information technology
- Increasingly capable machines
- Increasingly pervasive devices
- Increasingly connected machines

Although all are important and mutually reinforcing, it is the second – increasingly capable machines – that challenges the capabilities of humans the most. Many new capabilities of machines increasingly surpass humans on tasks previously understood to be uniquely human: "Machines are no longer confined to the grunt work" (Susskind & Susskind, p. 159). Importantly, these technologies do not need to replicate human abilities or processes to produce similar or superior results. "There are lots of ways of being smart that aren't being smart like us (Patrick Wintour)" (Susskind & Susskind, p. 164).

The Susskinds categorise 'increasingly capable machines' into four types:

- Big Data
- intelligent systems
- robotics
- affective computing

Big Data is the analysis of information the size of which precludes human processing, therefore Big Data can gather novel and valuable insights that were not previously available. This data includes existing datasets (e.g. passenger data from transport systems, traffic signal data) and that generated by new digital sensors on machines (e.g. vehicles, roads,

smartphones and other personal devices). This can generate useful predictions about future performance that are beyond those that professionals are able to make.
Big Data challenges professionals' expertise by being based on systematic, sophisticated and comprehensive analysis of massive datasets, beyond the information processing capabilities of professionals even if highly sophisticated. Big Data now can, and often does, surpass professional judgment.

The second type of digital technology whose capabilities are rapidly increasing in type and sophistication is 'intelligent systems'. IBM's AI-based computer system Watson is described in some detail as the best example of this, because it combines many AI technologies in different ways depending on the information processing task it is set. The AI technologies Watson uses include natural language processing, machine learning, speech-synthesis, game-playing, informational retrieval, intelligent search, knowledge processing and reasoning.

Furthermore, in 2015 IBM was already testing Watson's abilities at performing professional tasks (p. 165). On the basis of Watson's performance, the Susskinds state: "The day will come, for most professional problems, when users will be able to describe their difficulties in natural language to a computer system on the internet and receive a reasoned response, useful advice, and polished supporting documents, all to the standard of an expert professional practitioner" (p. 166).

The third type of digital technology whose capabilities are rapidly increasing in type and sophistication is robotics. Manufacturing has been deploying robots for many years, initially as devices controlled by humans while the task was being performed, then as 'cobots' performing a task jointly with humans, and then independently functioning machines. There were already 1.5 million industrial robots in 2015.

Two examples of the sophistication of robots show the challenge to professional tasks involving physical or manual dexterity: a tele-surgery, e.g. a surgeon in New York operating on a patient in France via a robot called Zeus; and robotic sensing, the ability to detect physiological changes in humans and other animals. Professional tasks involving physical movement or manual performance are therefore also threatened by this form of digital technology.

The fourth form of digital technology that is undergoing rapid change in the type of tasks it is able to perform is 'affective computing' – systems that can detect the emotions of others (e.g. through facial pattern recognition, or detection of heart rate via physiological sensors), and also express 'emotions' to others (e.g. modulate the way they convey information appropriate to the emotion they detected). Affective computing technologies are most often combined with robotics (as in 'digital companion robots' to assist the elderly in Japan) but could be combined with other digital technologies (e.g. intelligent systems).

The Susskinds see affective computing as a threat to those aspects of a professional's role or task that require them to 'read' and respond appropriately to their human clients, and to the claim of many professionals that the key aspect of their role is being able to integrate highly sophisticated technical knowledge with interpersonal awareness and sensitivity.

The 'digital' part of the Susskinds' argument can therefore be summarised as: there are four types of digital technology undergoing qualitative change in the type of tasks they can perform, so that individually these categories can outperform many tasks previously understood to be uniquely human. However, these technologies can also be combined, which will increase the type of qualitative change in digital capability still further. In addition, the digitisation of knowledge will release widespread latent demand for knowledge that was previously unaffordable.

This presents a profound challenge to 'the professions' because of the features of knowledge as an economic entity.

1.1.2. Knowledge as an economic commodity

The Susskinds' economic argument is summarised below:

- ‘The professions’, broadly defined, are those domains of work whose purpose is the production and distribution of specialised knowledge.
- Knowledge, as an economic entity, has four unique characteristics that make any business model based on it vulnerable to competition, because knowledge is:
  - Non-rivalrous – one person’s use of a piece of knowledge does not prevent another person’s use of it (e.g. if I eat an apple, no one else can eat that apple; if I read a book another person can still read the book after me).
  - Non-excludable – it is difficult to prevent non-payers from using it (e.g. even if I paid to read a book, I can pass the knowledge I learnt from it to others without my paying again or the others paying at all).
  - Cumulative – the use and re-use of knowledge increases its value, and different pieces of knowledge can be combined to derive new knowledge and new economic value (e.g. so if I have some knowledge about bicycles from one source, and gain some more from another, I could combine it to create some new useful knowledge I didn’t previously have).
  - Easily digitised – the ability of knowledge to be produced, stored, retrieved and distributed using digital technologies (e.g. an apple can’t be converted into digital form and still be edible or contain seeds; however, the knowledge in a book is equally useful whether it’s in paper form or electronic form).
- The way these characteristics influence the production and sharing of knowledge depends on the methods a society uses for producing, recording, accessing and sharing that knowledge. These methods have changed over time, from an oral society, to a script-based society, to a print-based society, to our current emerging digital technology society.
- ‘The professions’, broadly defined, are based on long-established conventions within society between the producers of expert knowledge, its users, and society that were mostly created in a print-based society. It involves allocations of tasks and bundling of services and agreed ‘reasonable’ prices, which are only commercially viable in a print-based society.

Implications of the combination of the digital technology and economic analysis arguments

Combining these two arguments produces the following summary of the professions’ predicament: hitherto, most business models for professional services have been based on a cross-subsidy between routine, low cost, tasks typically performed by junior staff, and the most complex, creative, unpredictable and, hence, expensive tasks performed by senior professionals. By outcompeting humans, especially on routine tasks, digital technologies are removing a revenue stream that helped to ensure commercial viability for professional services firms as a whole. To make good this loss, professionals need to be able to charge customers high prices for new services.

Using this analysis, the Susskinds propose a model of the evolution of professional work in which digital technologies have the automatic upper hand over print-based methods.

Internal to a profession | External to a profession

|->Charge online

Craft -> Standardisation -> Systematisation |->No charge online

|->Commons

Figure 1 (Taken from Figure 5.1, p. 197, Susskind and Susskind, 2015)

As professional tasks become less bespoke and more amenable to being routinised, they require decreasing levels of professional skill. Once a professional task has become systematised and digitised, it is not essential that it be performed by a professional. For instance, in the early 19th century, far fewer people would have been able to perform calculus than today, and this would have been a ‘craft’ or bespoke skill. However, over time it became more widespread as a skill and hence was performed as a more standardised task. More recently software has been able to perform this task, and now you can solve calculus problems online for free.

Other examples include choice of materials in structural engineering design, followed by structural engineering standards, then section tables with capacities, and now there is the wiki building site for sizes of columns you will need, although you may still need to refer to BCSA (British Constructional Steelwork Association Ltd); the shift from bespoke kitchen design to kitchen design software in IKEA; or the shift from portraiture to online digital photography.

As a result, Susskind and Susskind argue that the best way for professionals to respond in the short and medium term is through the development of new products and services that deal with less 'routiniseable' work – even though Susskind and Susskind anticipate machines will become experts at these tasks too, several decades hence.

Future task types and orientations that professionals should adopt in response include:

- far greater focus on what customers want
- work that is more proactive than reactive (e.g. ways to identify and manage risk)
- the mastery of massive bodies of data (including identifying, building, acquiring and trading datasets with others)
- being part of teams developing computerised systems
- improving communication skills and the value that is derived from that (e.g. identification of latent demand, unrecognised problems)

This will call for increasingly multidisciplinary work because "'everyday' problems are less structured than is suggested by the clear boundaries among our professions" (p. 118).

Ultimately, because of the four characteristics of knowledge, Susskind and Susskind predict widespread technological unemployment for the professions. Most professionals will be replaced by less expert people and high-performing systems – and increasingly the latter.

There are two objections to Susskind and Susskind's argument: the inability of digital technologies to replicate human abilities; and Susskind and Susskind's analysis being based too much on economic theory rather than observations of reality. Both objections are dismissed by the authors.

For those inclined to dismiss the transformative nature of advances in digital technologies on the basis that 'computers can't replicate human thinking and scientific progress in this area shows many significant challenges', they emphasise the logical errors of this 'AI fallacy'. Even if digital technologies cannot ever replicate human thinking, this does not mean that they won't be able to (out)perform the tasks to which human thinking has previously been applied. Instead, digital technologies may use different methods to solve these problems with superior outputs (e.g. using Big Data).

For those inclined to dismiss the economic analysis as being too theoretical and, therefore, unlikely to happen in reality, they provide a 54-page review of the many ways in which digital technologies were already in 2013 transforming professional tasks and the professions themselves, in eight different professions (health, education, divinity, the law, journalism, management consulting, tax and audit, architecture).

1.2 Recommended new business models

This sub-section includes five areas for consideration regarding new business models:

> *Section 1.2.1 'Misunderstanding the need for business model change' addresses the situation where the built environment profession accepts the need to adopt new types of tasks, but does so without recognising the need for a concomitant business model change.*
> *Section 1.2.2 'Recommended changes to business models based on historical accounts of relevant sectors'*
> *Section 1.2.3 'Suggestions for going forward with limited changes to existing business models'*

Section 1.2.4 'Detailed business model recommendations' made by the Royal Academy of Engineering, Association for Consultancy and Engineering and Project 13 (initiated by ICE and Infrastructure Client Group).
Section 1.2.5 'Wider context for business model ethos'

1.2.1 Misunderstanding the need for business model change

Some authors, including some within the engineering profession, have recognised the need for professional tasks to change, but do so without recognising the concomitant business model change.

In a recent volume focusing on the '2040 Vision' for engineering (IStructE, 2020), several authors exhort engineers to "envision a different future for your business" (Burrows, IStructE, 2020, p. 42), or recommend increased empathy, creativity, or collaboration skills (Clark & Ibell, IStructE, 2020; Bell, IStructE, 2020), but without relating these to a business model change that will enable these changes.

Business school professors sometimes appear similarly oblivious to this challenge. Fischer (2015) argues that, since digital technology will provide the credibility and reliability of professional services in the future, professionals will be able to retain high-value business models by focusing on high-quality interpersonal skills and relationships with customers, although the question remains whether customers will still be prepared to pay high prices for such skills.

This difficulty in recognising business model development as a necessary skill within engineering and construction firms has been recognised as a challenge for the sector by several authors (Smyth 2018; ACE 2019b; PCubed). Hedley Smyth's historical review, Castles in the Air? The Evolution of British Main Contractors, which surveys British construction firm development between 1936 and 2015, describes the repeated failures of management in this regard. Between 1955 and 1968, he writes, management was "reactive… defensive… and focusing upon two prime units of management thinking" (p.17): types of projects e.g. airports or housing; or ways to improve individual projects. Managers were still doing this between 1968 and 1980; and between 1980 and 2015, British construction firms lost market share in international markets to overseas firms.

Some of Smyth's recommendations relate directly to functions necessary for the development of viable business models: that management give specific attention to short-, medium- and long-term strategic planning, and that it should focus on the development of the capabilities of the firm as a whole that distinguish it from others in the market (as opposed to focusing only on improving individual projects).

Similarly, in Future of Consultancy, the Association for Consultancy and Engineering (ACE) recognises that the development of business model skills within engineering and consultancy firms is essential if they are to derive the maximum benefit from value-based business models, and that this is a new skill for this sector. Furthermore, ACE recognises that construction firms, as well as engineering and consultancy firms, will need to develop new business models. Engineering and consultancy firms will need to help construction firms achieve this and ACE calls for new academic training for engineers in this new skill.

At the time of writing, PCubed and Dr Janet Smart at Said Business School, Oxford University, were running a research project with engineering firms about capabilities in developing service-based business models (PCubed, 2020), emphasising that this was an essential, but still novel, capability for the future success of engineering.

However, this may not be so much a totally new skill as much as a forgotten one in a new 21st-century context. The need for new business models to achieve global challenges such as climate change and sustainability leads de Hoog (IStructE, 2020) to remind engineers of Brunel in the 19th century. Not only did Brunel have technical prowess, he was also exemplary because of his entrepreneurial skills: identifying novel engineering opportunities and then corralling or finding new sources of economic value to pay for them. Engineers should follow his technical prowess and his entrepreneurship, now and in the future.

1.2.2 Recommended changes based on historical accounts of relevant sectors

Both Foxell and Smyth provide historical accounts of the interplay of different firms and organisations (e.g. different types of professions or businesses, government, domestic and international clients), and the business models between them, in relevant sectors. Both conclude with business model recommendations based on these historical analyses.

Business models comprise different components – products, services, supplier and customer relationships – structured in unique ways to generate value. Changes to any one of these can be so significant that they necessitate the creation of new business models. Accordingly, the discussion sometimes includes business model components where their inclusion is likely to necessitate such change.

Simon Foxell's very detailed book, Professionalism for the Built Environment, focuses on the built environment sector rather than civil engineering per se. He makes nine recommendations about built environment services to make the sector fit for the future, and four of them are about business models:

- effective maintenance and repair regimes (especially with the use of BIM and massive datasets to improve both operations and design)
- providing 'project risk as a service' when that offers significant value to clients
- environmental skills and value (despite the challenges of government U-turns and policy reversals, professionals need to be trained in this area before it becomes indispensable, or risk considerable loss of value)
- emphasising, developing and maintaining an ethical reputation with increased buy-in from a wider range of stakeholders declining work if necessary

In addition, professionals "need to retain their ability to think through unforeseen problems and offer the right guidance" (p. 277).

Foxell recognises some significant challenges in achieving these recommendations. For instance, BIM and massive datasets can only be transformative if data is collected, analysed and shared. Another issue is that human execution will become only necessary for problems that require creativity and ingenuity as well as technical ability, while projects requiring such skills are rare and unusual. Nevertheless, he says, "if transformation is not led from inside the professions, it will be imposed externally and possibly brutally" (p. 270).

Smyth (2018), in describing the significant changes in the construction sector since 1936, many of them beneficial (including diversification, increasingly professional management and construction workers), also identifies repeated missed opportunities such as a failure to invest long-term in new developing; over-reliance on cashflow management to drive profitability; failure to exploit the increasing professionalism of the construction workforce; and a failure of management (and much construction sector advice and thinking) to focus on the development of specific capabilities (as opposed to project management expertise).

Smyth's recommendations all relate to the development of better current and future business models. He recommends: new business models that deliver social, economic and environmental value to clients; short-, medium-, and long-term planning to include investment, business development and marketing so that market and individual client needs are met; and the development of integration between firms, suppliers and subcontractors at the point of delivery.

1.2.3 Suggestions for limited business model change

Several authors have proposed changes that would affect business models but in a limited way.

The huge variety of different technologies now deployed on construction sites, and the continued increase of this in the future, reveals a need for new 'specialist-generalist' engineers (see later sections on sustainability and productivity)

(McGilvery and Pierce, IStructE, 2020). These engineers will be highly skilled multi-technical experts able to identify and resolve any operational gaps between multiple technologies on site. This will reduce and ultimately prevent construction delays currently experienced owing to unrecognised mismatches in performance between different technologies.

Specialist-generalist engineers will join three existing types of project professionals – commercial lead, design lead, construction lead – and business models will need to adapt to include them.

In Engineering priorities for our future economy and society (RAE, NEPC, 2019), digital technology is seen as likely to have a strong impact on society, including significant increases in unemployment. Consequently, substantial changes in business models are needed, including funding mechanisms for engineering projects; collaborative working, especially in relation to digital data; and assistance to help people identify new career directions (and therefore the underlying likely viable business models).

However, one report cautions that the impact of disruptive business models may be less than predicted owing to the high costs of accessing the patent system on which most innovations, including digital ones, depend (Raconteur, 2018). High costs for patenting and knowledge licensing are particularly prohibitive for small- and medium-sized enterprises (SMEs), which can prevent many start-ups from accessing digital technology patents that will help them to advance. For both digital technologies and SMEs to reach their potential, the business model to protect patents needs to change significantly.

1.2.4 Detailed business model recommendations

The Royal Academy of Engineering (RAE) and ACE have produced detailed considerations for business models for (civil) engineering: Project 13 can be understood as a whole-sector approach to the creation of new business models and provides the greatest insight into the future civil engineer's likely business model.

Royal Academy of Engineering (RAE)

The RAE's 2016 report, Engineering a Better World: Achieving the UN's Sustainable Development Goals (SDGs), describes many examples where novel business models are already enabling engineers to deliver sustainable infrastructure, sometimes to completely new markets, and often via the collection and transmission of digital data. For instance, new business models already enabled through digital data support high-precision use of water via GPS, data monitoring of existing water infrastructure assets in the developing world to prevent redundant or duplicate infrastructure commissioning; and new energy technologies for mini-grids and solar-diesel hybrid rental farms for remote communities.

However, achieving the SDGs also requires more significant changes to business models such as increasing or changing the financing stakeholders or funding mechanisms, or overall project requirements. For instance, protecting society's assets from the effects of climate change will require 'failing safe' in all resilience planning, and designing to outcomes. To achieve responsible consumption and production, eco-efficiency in factories will help, but businesses must also "commit to redesigning their entire value chain" (p. 29).

Sharing data with other organisations can produce very large benefits for both the provider of the data and its novel users, and hence this should happen more. For instance, Transport for London shared some of its data with third parties to develop apps, which resulted in increased benefits to customers (apps with new ways to use this data) and improved TfL's operational performance, estimated at producing 58 times more value than the initial project cost (p. 23).

Association for Consultancy and Engineering (ACE)

ACE has recognised the profound significance of the pressures for business model change in engineering and has dedicated several recent reports to this issue (ACE 2019a, b, c). One report focuses on the benefits of using value-based business models in detail (ACE 2019b). Value-based business models require engineering consultancies to become far better at 'teasing out' the definition of value that clients have and need. Viable business models will be built around 'value rather than volume', and increasing focus on deriving value from outputs or, even better, outcomes (ACE 2019b, p. 5).

Engineers need to recognise that there are five different types of capital that clients may have available to use, or firms work to improve, and explicitly include them in all stages of projects:

- natural capital – the natural environment, natural resources, and ecological services from those
- social capital – societal groups, communities, schools, businesses, voluntary organisations etc
- manufactured capital – materials and goods or assets that are needed to input to the process
- financial capital – a traditional economic measure of value which is intrinsically linked to natural, social, and manufactured capital
- human capital – the health, skills and motivation of individuals needed for a productive economy

In addition, engineering needs to realign the relative weight of fee and performance payments on projects, depending on the nature of the business model being delivered. For instance, in transactional, short-term business models where the client pays for technical expertise alone, the majority of the payment will come from a pre-arranged fee. However, for more value-based collaborative, longer-term business models, the majority of client payments will come from engineering firm performance, with a proportionately smaller pre-arranged fee.

ACE argues that, although collaborative business models disrupt the current areas of competition for the industry overall and make consulting work less people dependent, they have numerous benefits: they enable better pricing for reinvestment in the consultancy; they create "sustainable businesses delivering repeatable work/products while improving their productivity"; and "work is increasingly exportable as it is less people dependent" (ACE 2019b).

However, realising these benefits requires several other changes:

- Changes to professional indemnity insurance that consultancy firms are insured for the different type of risk involved in outcomes-defined contracts compared with input- or output-defined contracts. ACE notes that the IPA and Construction Innovation Hub have been working on the insurance contract changes needed to achieve this.
- A transparent supplier performance system for clients, as well as engineers, to inspect – digital technology enables this.
- Contractors will also need to change their business models, and consulting engineers should support contractors in this task.
- Moving an engineering consultancy into new markets or different business models is an essential new skill for engineers for which new academic training is required.

ACE also uses its analysis of business model types (see Fig 2): to identify three types of markets for UK consultancy and engineering: planning and placemaking; delivery of integrated projects; data-led asset performance (ACE 2019c). In turn, these suggest that the following 10 global markets should be prioritised: the US, India, Indonesia, Germany, Australia, Canada, Mexico, Saudi Arabia, Malaysia and Ethiopia.

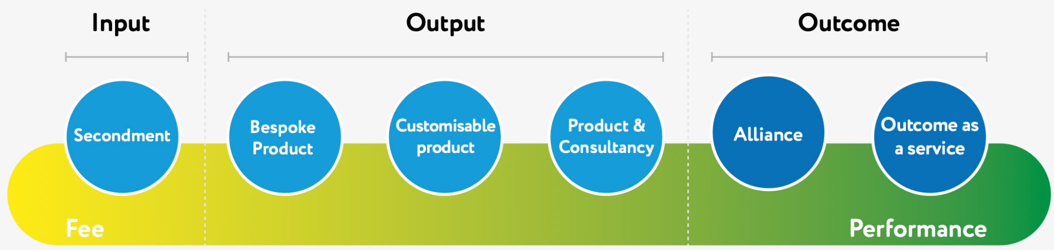


Fig. 2 The framework of potential business models for consultancy businesses in future

Figure 2 (taken from ACE 2019b, p. 5)

Project 13

Project 13 is an industry-led "blueprint for the future" initiated by ICE and the Infrastructure Client Group, providing clear analysis of how the predominant business model for construction is causing problems, a new model that aligns business interests far more effectively, and extensive practical materials for infrastructure leaders to use.

Core to Project 13 is the recognition that the productivity and reliability of the construction sector is poor compared with other sectors and must improve. A focus on reducing costs rather than outcomes, and negotiating transactional deals on a project-by-project basis, has entrenched poor productivity and low investment in skills. Project 13 recognises that this needs to change, and it will not happen without a total overhaul of the approach and methods for construction sector operation, hence the shift "from projects to enterprises".

This change is best achieved by changing behaviours, processes and commercial arrangements through incentivising performance (rather than work volumes) and measuring agreed delivery outcomes (again, rather than work volumes). These changes will affect everyone involved: the Project 13 Blueprint sets out the different roles of investors, owners, integrators, advisers and suppliers.

The 'enterprise' model includes five 'pillars' that are a necessary part of any such model: the presence of a 'capable owner'; appropriate governance; good organisation of actors within the enterprise; integration; and digital transformation (Project 13 Framework). A further 16 principles underlie the five pillars and offer different ways in which the pillars can be achieved. The Project 13 Commercial Handbook sets out six key commercial principles, and four steps for creating a commercial strategy.

The key commercial principles are: alignment of rewards and outcomes; rewarding mechanisms on the basis of exceeding outcomes – not lowest cost for components; asset owner or investors are not to transfer their risk to the supply chain; the application of the enterprise model at whatever scale – e.g. asset systems or asset portfolios – achieves the greatest benefits; a focus on relationships between stakeholders over longer time periods.

1.2.5 Wider context for business model ethos – finite and infinite game-playing

These reports and practical actions are happening within a wider context of debate about business models and purpose. There is an increasing emphasis within mainstream business thinking of the need for improved business models that address grand challenges – see for instance the September 2019 call by the Financial Times for a "reset" of capitalism (see also Deloitte, 2020). Debates about business purposes, and how those purposes can best be achieved, are widespread.

In this context, one very useful distinction is between finite games and infinite games (Simon Sinek, The Infinite Game, 2019). Sinek argues that businesses, and business models, are one or other of these two types, and that those based on an infinite game perspective are most likely to be successful in the long term.

While finite and infinite games share the need for two or more ‘players’, they have many significant differences. First, in a finite game the players are known and determined in advance; in an infinite game, it is not known who all the players are in advance, and players can change over time. Second, a finite game has agreed fixed rules, whereas in an infinite game there are conventions rather than rules and these can be changed at any point. Third, while finite games work towards a pre-agreed fixed end point which is win or lose, the purpose of an infinite game is to keep playing the game. There is no winning in an infinite game, and therefore the benefits of playing accrue to all players, not just the winner.

Finite and infinite games also need different skills. For an infinite game, the skills are: build a just cause; build trust in teams; study your worthy rivals; show existential flexibility; demonstrate courage to lead. Sinek has therefore argued that contemporary business confronts the choice between short-term finite games or using an infinite game approach in which all players – firms and customers – accrue benefits and keep playing. Long-term thinking is likely to be more successful.

2 PROFILE OF CONSTRUCTION WORKERS

This section will summarise why the profile of construction workers is a key challenge for the sector, and then consider the proposals for resolving this issue made by: the Construction Leadership Council; the RAE; the National Centre for Universities and Business; Raconteur reports from The Times and Sunday Times; and two pieces of academic research.

2.1 Why is construction worker profile a problem?

The profile of construction workers is a key challenge for the sector, for four reasons. First, difficulties in training and recruiting new entrants have been longstanding over several decades, as evidenced by the fact that 30% of construction contractor workers are expected to retire in the next 10 years (The Perkins Review, 2013). The RAE report Engineering priorities for our future economy and society contains some stark figures about the shortage of engineers in the UK: an annual shortfall of 59,000 engineering graduates and technicians, and 124,000 for engineers and technicians with core engineering skills. In addition, 50% of roles in the Shortage Occupation List are in engineering.

The Construction Leadership Council Future Skills Report recognises equally concerning workforce shortage issues in the construction contracting workforce, including skewed age distribution across the sector, 8% of workers being non-UK nationals and hence facing an uncertain future in the UK, and a serious shortage of workers with traditional trades. In addition, given civil engineering’s ambition to become far more representative of gender, ethnic and cultural diversity, there is the possibility of construction becoming a more attractive sector for workers from these backgrounds. Similarly, the increased need for creativity, digital and soft skills for civil engineers could also have knock-on benefits for recruitment into construction.

The second reason why construction worker profile is a problem is the lack of representativeness of the sector. The rates of women and people from ethnic minority backgrounds (BAME) within engineering are poor: a 2007 survey showed that the UK had the lowest proportion of female engineering professionals among 27 other European countries (Perkins, 2013). This remained a problem six years later – the follow-up to the Perkins Review found that female participation in the profession was only 12% compared with female participation of 46.9% in the overall UK workforce. In terms of ethnicity, only 8.1% of engineering professionals are from BAME backgrounds, compared with 12.7% in non-engineering sectors and 12.2% in the general population (Perkins, 2019).

The third reason why construction worker profile is a problem is the urgent need for new skills, and a profession actively engaged in lifelong learning, to exploit the opportunities for the sector presented by new digital technologies (e.g. Mace, 2017; AECOM, 2019; Deloitte, 2020) and delivering on the UN's Sustainable Development Goals (RAE, 2018).

Lastly, the construction sector suffers from a negative image, of being old men working "in hard hats and mucky boots" (Sheffield, 2019) at a time when few want to work in such conditions. The RAE has been working to identify and improve the reasons for negative public perceptions of engineering for some time (Public perceptions of engineering, RAE 2007).

An ageing, highly disproportionately male and disproportionately white workforce is not sufficient to meet these challenges. Negative images are a barrier to the recruitment of young people into the construction sector (Attitudes to Engineering survey, BEIS, 2014; Public perceptions of engineering, RAE 2007). Consequently, several reports have made recommendations for significant change to transform recruitment methods, and the identity of those recruited, into engineering or construction.

2.2 Construction Leadership Council (CLC) study

The Construction Leadership Council's Future Skills Report is particularly concerned about the difficulties of recruiting into the construction sector. It recognises four key factors that are restricting workforce diversity and skill level:

- the fragmentation of the industry and low levels of collaboration between construction workers and other sectors
- the lack of widespread direct employment and worker training so that economic incentives for investing in the long-term needs of the construction sector are not aligned effectively
- short-term procurement practices, especially in relation to skilled workers
- the absence of high-quality training in digital skills

The CLC argues that construction workforce diversity can be significantly improved by greater use of direct employment contracts rather than subcontracting; greater use of smart design methods early on in projects as a way of creating demand for highly skilled employees; and by updating industry training to include digital skills as standard. In addition, construction workforce employees should be more socially diverse, for example in terms of gender and ethnicity.

2.3 The National Centre for Universities and Business (NCUB) report

The NCUB's Talent 2050 report expresses frustration with the length of time the engineering sector has been complaining about the lack of recruits, and urges a completely new approach. Rather than thinking in terms of a 'training pipeline', the NCUB urges that UK school, college, university and general populations be understood in terms of a 'reservoir of talent' that contains numerous diverse skills and talents that can be used in new ways to solve 21st-century engineering challenges and optimise the benefits derived from digital technologies.

This new approach is necessary to move away from an obsession with university education as the sole or preferred route into the profession, which has resulted in other sectors of the population being neglected by priorities in engineering education.

The NCUB also argues that recruiters should give less emphasis to the length of time a candidate has (or has not) spent working in the sector, and be more open to recruitment from outside the sector. NCUB's report recognises that people with highly valuable skills – especially digital skills – may currently work in other sectors but need to be enticed into engineering. Requiring that they study to become engineers first when they already have skills engineering needs is self-defeating. Equally, the NCUB recognises that people may move from engineering to work in other sectors: this should not be seen as a failure of the training pipeline, but a continuation of the 'reservoir of talent'.

Accordingly, the report's specific recommendations are for greater flexibility in three areas of engineering:

- To remove recruitment barriers and bottlenecks, which needs to include a change in perception by recruiters of there being a 'reservoir of talent', and for applicants to be valued on the basis of their ability to learn rather than past performance.
- Changes to all types of education so that digital skills and environmental issues are standard core components, with education preparing all learners for interdisciplinary working. This could require some changes to the traditional civil engineering degree.
- Far greater exchange of employees between sectors rather than people staying 'stuck' within a single discipline and approach. This needs to apply as much to SMEs and gig economy workers as large corporations.

2.4 Royal Academy of Engineering (RAE)

Two recent RAE reports (Engineering priorities for our future economy and society; Automation and the future of work) emphasise the importance of properly costed further education and apprenticeships as routes into engineering and infrastructure and also the need for employers to have flexibility in the way they spend the Apprenticeship Levy, as part of a coherent strategy to allow engineering to flourish throughout the UK.

From the perspective of likely impacts of automation, the RAE also emphasises the importance of apprenticeships and lifelong learning, and especially the need to engage new adult learners into lifelong learning. The RAE also suggests that working hours should be reduced for those with high-demand digital skills as a way of increasing uptake from traditionally-resistant sectors and demographics (such as those found traditionally in construction), along with support for people in identifying new career directions. (It is arguable that these practices should be for all in the construction sector, not only those with highly-sought digital skills, although if this were the case the need for additional incentives for workers with shortage skills would still remain).

From the perspective of how engineering can enable the delivery of the UN's Sustainable Development Goals globally, the RAE also highlights the importance of gender equality (see section 7) in all sorts of inputs to development projects, including stakeholder engagement and professional roles not only on natural justice grounds but also because this improves the quality of inputs and feedback on projects.

2.5 Raconteur Reports

Two focused reports by the 'Raconteur' series in The Times and The Sunday Times, on The future of engineering 2018 and The future of construction 2019 respectively, both emphasise multiple diversity issues for the construction sector. In addition to generally recognised diversity issues such as gender and ethnicity, and the need for greater communication and team-working skills, they also recommend that the construction sector considers more flexible working practices (e.g. so construction workers can look after aged relatives), recognises the need for a balance of employees with introvert/extravert personalities, measures the social mobility of its employees, and makes adjustments to employ people who may have English as a second or third language. It is argued that to address these issues, investment by engineering/consultancy and construction firms themselves is needed rather than a sole reliance on support mechanisms from the government.

Lastly, the reports describe successful instances of recruiting people with high-level digital skills from the gaming industry and that construction and engineering has plenty of attractive professional challenges for such people, but that the sector needs to present itself more effectively to attract the necessary inter-sectoral transfer. These reports therefore recognise the need for wide-ranging actions to improve recruitment into the construction sector, and to increase workforce diversity which they define in a pleasingly broad way.

2.6 Academic reports

Naoum et al (2019) compared men and women's perceptions of work practices in UK construction companies, and found that, although women were more likely to show a changeable pattern of job roles than men, a pattern that is related to fluctuations in women's self-esteem, both men and women valued "improved flexible working arrangements", "transparent promotion criteria", "return to work training" and "outreach programmes to schools" as the most effective initiatives to retain women. However, marked 'dips' in women's career paths and their self-perception of their careers were closely related to the age range of 35-44, which are also the most common child-bearing years for female engineers.

Both women and men felt that female participation in construction would remain at about 10% – and 70.9% of women felt that female recruitment was still a significant issue. This suggests that methods often thought to be particularly effective as a way of recruiting women into construction companies would be equally attractive to existing and new male workers, which should help the roll-out of such practices throughout construction, helping recruitment sooner rather than later.

Physical and mental wellbeing at work are recognised as elements of a modern healthy environment, but this can be challenging to achieve in construction. A recent ICE report (Costs of occupational ill-health in construction) found that the annual cost of employee ill-health in the UK construction sector was £848m. The demanding nature of work onsite means that it is important construction workers are in good physical and mental health.

Karakhan et al (2020), from the US, used a literature review, semi-structured interviews, and a detailed expert survey to develop a psychometric tool to identify how construction workers are coping with physical, financial and mental challenges. However, an older, male, non-university educated workforce is often reluctant to discuss such issues. The development of this tool is therefore a step forward in improving the wellbeing of individual workers as well as helping to change the workplace culture to one that is more welcoming and current with mainstream cultural norms. Again, this should help recruitment to become more diverse.

3 DIGITAL

This section focuses on sector overviews of digital transformation, covering the following topics: better use of existing technology; automation and AI; 4th Industrial Revolution; learning to share data; public trust; new skills for a wider industry; lifelong learning and how to usher in digital transformation – start small; digitisation hype and policy. Wherever possible, examples from civil engineering or infrastructure have been used; where this was not possible, examples from similar sectors (e.g. manufacturing) have been used.

3.1 Sector Overviews of Digital Transformation

Digital technology is changing the way the public interacts with infrastructure and how infrastructure owners sell their service. For example, 'mobility as a service' is where convenience is key and commuters select and pay for their travel service on a single platform in as few steps as possible. Helsinki and Stockholm are implementing this 'integrated mobility' approach now, and Singapore will follow soon (AECOM, 2019).

Balfour Beatty's report, Innovation 2050 – A Digital Future for the Infrastructure Industry (Balfour Beatty, 2017), offers a reminder that, accompanying digital transformation and other challenges with increased urbanisation comes an increase in demand for energy consumption owing to processing and using data. There is also the challenge of ensuring that real-time (5G) connectivity actually works. Another challenge centres on the theme of data privacy against the benefits of using mass data, exacerbated by concerns for cybersecurity.

The report makes 10 predictions that will accompany a successful digital future:

1. The industry will become increasingly focused on innovation and both contractors and customers will become less risk-averse.

2. The shape and offer of the infrastructure industry will change significantly, with new business models, products and services.
3. Infrastructure will move on from concrete and steel to include new materials.
4. New jobs and industries will be created – and some will disappear.
5. Thinking only about design and construction will become an outdated concept as infrastructure becomes multifunctional.
6. Robots will become more prevalent in construction.
7. Construction will get faster, using 3D and 4D printing, and self-transforming objects which self-assemble.
8. New, disruptive ideas will emerge, for making mass transit faster, safer and less damaging to the environment.
9. We will increasingly use wearable technology such as exoskeletons (e.g. Balfour Beatty's subsidiary, Gammon Construction, is using exoskeleton systems in Hong Kong to increase productivity and make easier tasks involving heavy lifting and repetition).
10. Direct neural control over devices and vehicles will be accessible to the industry (implantable microchips).

3.2 Better use of existing digital technology

In every aspect of our lives, digitisation is taking hold (Ericsson, 2019). Transport for London's digital payment card Oyster started in 2003 and is seen as a big success, ushering in even smoother contactless payment options with normal debit cards, speeding up passenger flow and reducing operational costs. Also, 58% of Londoners now use mobile apps to keep up-to-date with public transport services, saving time and increasing passenger satisfaction.

Given this success with digital technology for Transport for London's customers and operators, similar benefits are expected for other consumer-facing digital technologies, such as domestic smart meters. Used well, these will drive efficiencies in domestic energy consumption. Other examples of public-facing digital technologies that already exist are high-speed fibre optic broadband, electric car charging stations and digital water meters. Again, these exist in some places worldwide already, but are expected to become widespread and hence improve connectivity, electric car take-up and water usage respectively (AECOM, 2019)

Ericsson's smart manufacturing and warehousing report, Unlocking the value of Industry 4.0, discusses how mobile networks, based on 4G and 5G, enable a diverse set of Industry 4.0 tools for efficiency gains in logistics tracking, including condition-based monitoring (CBM), real-time location system (RTLS)/asset tracking, inventory management, augmented reality (AR) glasses, wearables, building automation, robotics, and more.

It is claimed that profits can be increased, over just five years, by 5-12% by implementing some of these, and in one case a 14-fold return on investment. It suggests organisations think more holistically and calculate not just the return on investment (ROI) for an implemented technology, but also the cost of inaction to quantify the impact of inefficiencies.

5G has become a necessity, according to the National Infrastructure Commission in its 2016 report Connected Future and therefore should be rolled out by the government as soon as possible for the benefit of the whole economy, paying attention to rural areas where coverage is most lacking. Until this is addressed, even the digital technologies that already exist will face barriers to their adoption in rural areas. 5G should be considered as part of a wider ecosystem of mobile connectivity, not in isolation. It can then form the basis for market opportunities for connected and autonomous vehicles and the Internet of Things (NIC, 2016).

3.3 Automation and artificial intelligence

McKinsey's 2018 report Skill shift: Automation and the future of the workforce found that business was beginning to understand that AI is an opportunity, not a threat. The report states that demand for technological skills is set to rise 55% by 2030, so there is a big upskilling job to be done. Heathrow's Phil Wilbraham writes: "Automation will increase, and make it easier to book seamless journeys, from choosing your flight to checking in baggage. I see a time where your phone is the thing that helps you find the way through airport buildings and traditional signage becomes less prevalent" (AECOM 2019. p. 27).

Within construction, at least 10 different trades are expected to become very highly automated, including not only labourers, roofers and floorers but also specialist building operatives, plant operatives and steel erectors/structural fabricators (Mace, 2017).

Automation and artificial intelligence are changing the way we work as people increasingly interact with machines in the workplace. For instance, Ericsson reports that humans and 'cobots' working together on automotive assembly lines has not only improved productivity but also health and safety (Ericsson, 2019). However, the pace of change is going to increase. Automation will speed up the transformational shift in workforce skills required. Social and emotional skills, such as leadership and managing others, as well as higher cognitive skills, especially creativity, will be more in demand.

AI is expected to be used to revolutionise operational decision-making, with live data making for better-quality decisions. The potential economic gains are significant. The RAE's report Automation and the Future of Work (RAE, 2019) estimates that AI could increase the value of UK manufacturing by 2027 by up to 14%, and add £630bn to the UK economy by 2035. This would increase the annual growth rate of GVA (gross value added) from 2.5% to 3.9%.

Increased digitisation will also increase customised manufacturing, according to PwC's Digital Champions report (PwC, 2018) although this does not provide details of types of customisation or manufacturing type. However, only 9% of companies have already implemented artificial intelligence applications to improve operational decision-making.

3.4 The Fourth Industrial Revolution

The National Infrastructure Delivery Plan 2016-2021 outlines the need for two bodies to provide a comprehensive approach to infrastructure in the short term (the Infrastructure and Projects Authority to 2020-21) and the long term (National Infrastructure Commission to 2050) and details the £483bn infrastructure pipeline investment to 2020-21. The plan describes actions that need to be taken, including government support and funding, for the UK to become a world leader in 5G technology: delivering reliable and high-quality broadband connections which would support growth in productivity, efficiency and work for the whole economy. According to the IPA, "94% of small business owners consider a reliable internet connection critical to the success of their business" (IPA, 2016).

The plan also highlights the desire to develop digital standards for the construction sector – Building Information Modelling 3 and beyond – to save money in infrastructure operation and have the UK lead the world in digital construction.

The IMechE report, Industry 4.0 – Transforming Agility and Productivity, discusses INDUSTRIE 4.0, the German government's project advising it on the fourth industrial revolution strategy. This project outlines the marketing opportunities for Germany to establish itself as a leading manufacturing country in technology, in the automation of manufacturing, machine-to-machine and machine-to-product communication, the industrial internet and technology needed for mass customisation of production. It explains that customers previously sought the cheapest products, but now favour more emotional and customised products even if that sometimes costs more. This suggests that future construction will also include more customised products and services.

Digital factories enable customisation because they are more productive, enable cheaper product variation and customisation, have better quality control and consistency, and also have more efficient supply chains. IMechE's report gives an example of a company using data well, with increasingly sophisticated measuring and tracking technology and general upskilling of employees (to be able to programme machines) to achieve a more efficient factory for medical devices. However, this also suggests a potential vulnerability for construction, in that if it does not collaborate more closely with manufacturing it will be overtaken by digital manufacturing that can produce customised products more easily.

"What we thought were top-of-the-range measuring capabilities in 2005 are now a distant memory to the coordinate measuring machines (CMM) and laser measuring systems we now have at our disposal. Access to data around our factory has become the norm, with computer terminals being installed in all manufacturing, assembly, commissioning and test departments. This access to data goes way beyond the technical support that staff require, but also allows full business communication," says Warren Limbert, managing director of Lambert Engineering.

KPMG's report Beyond the hype: Separating ambition from reality in i4.0 is based on detailed interviews and visits to senior executives in industrial manufacturing firms in eight different countries in Asia-Pacific, Europe and the US, and five different revenue bands (from less than $1bn to greater than $25bn). KPMG's purpose was to find out what separates the i4.0 leading firms from the follower firms – a similar question can be asked of civil engineers: are they leaders or followers? It found that deep shifts throughout the whole of each business including both product lifecycle and value chain were needed.

Although a few of the firms had comprehensive i4.0 strategies and were changing their business models, operating processes and value chains, most of the firms included in the research had not started making the more wide-ranging changes throughout the whole business, so most were not yet getting the most enterprise-level value from i4.0 (KPMG, 2017a). However, it is precisely the more wide-ranging changes that are needed to derive the optimum benefit from digitisation – a point that echoes the benefits of shifting to value-based or enterprise business models in the infrastructure sector. Indeed, some argue that the key difference between Industry 3.0 and Industry 4.0 is that the former uses digital technology piecemeal whereas Industry 4.0 uses digital technology to integrate all aspects of the value chain (PwC, 2018, p. 5).

Another KPMG report (KPMG 2017b) highlights that digital technologies need to be harnessed to find ways to improve efficiency, expand access and remove waste. Improving efficiency on projects will be a key future role for civil engineers. However, rather than focus on the next big thing, a good option could be simply to use the technology we have already to its maximum potential.

The Manufacturer: Industry 4.0 UK Readiness Report, written in conjunction with Oracle, outlines findings from a survey of manufacturers' feelings towards Industry 4.0 – which is a relatively new term, first coined in 2011 and something of an unknown. It could be called a fusion of new technologies, which, separately, have been poorly understood, but which manufacturers expect to increase productivity. For instance, the introduction of cobots in automative components manufacture has improved geometric dimensioning and tolerancing of components by 10% and paid for itself within four months (Ericsson, 2019).

In another survey of manufacturing businesses, 69% stated that Industry 4.0 was going to have a significant impact on their business, including operational functions such as customer orders, inventory status and equipment maintenance.

3.6 Learning to share data

To derive the greatest value from data, many different datasets need to be shared and combined among multiple organisations so this combined dataset can solve new problems. There are different ways of achieving this. Government open data platforms are seen as the bedrock on which useful, convenient tools for consumers and other users such as asset owners can be built. Such data should be used primarily for the 'public good' and should not exist in siloes. Another method of increasing the availability of data to share is through alliancing or enterprise business models, which are collaborative. Such models can unlock real-time data more widely, allowing different firms to share each other's data because they all share in a common enterprise.

Alternatively, many conglomerates feel that digitisation can drive more efficiency through the industry and, in some cases, this is leading to mergers and takeovers to become better positioned for this change (Shekhar, 2016). "We strongly feel that digitisation will be of optimum use in the service industry. Many inefficiencies can be taken out using digital technology in the service sector," says Bhanu Shekhar, chief digital officer at GE Power Middle East and Africa (Shekhar, 2016).

3.7 Public trust

Related to the use of data originating from the public is the way people are increasingly seeking greater involvement in decision-making over infrastructure (e.g. HS2, Heathrow). Sharing data can be a tool to convince people of a need for something more transparently. But also, by encouraging the public to be willing to share data, much better infrastructure designs can be achieved. For instance, in AECOM's The Future of Infrastructure report, 55% of Londoners have not had the chance to provide feedback on transport services during the past year, and 46% have not had the chance to provide feedback on public infrastructure projects more generally. More than a half of respondents (52%) believe that city officials take a short-term view of infrastructure planning, with 59% stating that large-scale transportation projects in the capital are usually delivered late (AECOM, 2019).

However, there is a fundamental goodwill to infrastructure that cities can tap into with social media and data capture and analysis to transform both infrastructure performance and public perceptions of their ability to provide feedback. The combination of social media with public data could be key to widening engineering audiences. There is evidence for this: AECOM says 47% of Londoners are happy to share their personal data with relevant city agencies to help improve things, and 37% of residents are willing to pay higher taxes to fund infrastructure improvements in their cities (AECOM, 2019).

This shows that data can not only be used to inform decision-making and be addressed directly to increase overall satisfaction levels, but also increase public perception of the construction sector and engineering projects.

3.8 New skills for a wider industry

ICE conducted a Professional Skills review in 2018 to identify key trends affecting the profession, based on face-to-face interviews with industry leaders and an online survey of members worldwide. It found that civil engineers' skill set was widening, and should widen further, to include neighbouring professions and skills in operation and maintenance, renewal and adapting, and decommissioning of infrastructure. In his inaugural address, ICE President 2019-20 Paul Sheffield reported that 90% of buildings and structures in use today are more than 20 years old (ICE, 2019) so maintenance and repair is very important for civil engineering (ICE, 2019d).

The idea of one qualification process that lasts a lifetime has been replaced with an impetus for a culture of continuous learning. This needs to become more deeply embedded and both engineers and the industry need to continuously review and update the skills requirements of civil engineers. Engineers can be seen as lacking in soft skills, but these are becoming increasingly important, with increasingly multidisciplinary work. Also, stakeholder engagement and the impact of digital technology are rising in importance (ICE, 2018) (Review, 2018).

In its 2018 report Skill shift: Automation and the future of the workforce, McKinsey agrees there will be a skills gap, in the next five years, for technological skills we know about (e.g. for complex data analysis or web development) and for newer skills for blockchain technology development. A blockchain is a single system in which a record of transactions made in a digital currency are maintained across several computers via a peer-to-peer network.

However, another McKinsey report (Future skills: Six approaches to close the skills gap) identifies a lack of underlying transparency regarding future skills training options. Focusing on Germany, it suggests that the skills gap can be addressed by systematically implementing a structure for future skills training, and that transparency and state and federal government collaboration must work together, transparently, to achieve this. Finland is often seen as a role model for education, and Finnish schools are moving to project-based learning instead of traditional classes in mathematics and history to familiarise students with collaborative working and help them to gain wider problem-solving skills (McKinsey, 2018) (Bughin, Hazan, Lund, Dahlström, Wiesinger, & Subramaniam, 2018).

3.9 BIM

3.9.1 BIM context

Building information modelling (BIM) is a process involving the generation and management of digital representations of infrastructure assets (ICE 2016). These data models are used to gain greater efficiency: savings from better data use including reduced design changes and requests for information, fewer changes on site, less materials used, waste and time needed for construction, and increased safety and energy efficiency (ICE, 2015).

The UK has been encouraging the industry to become smarter with data since at least the introduction of the UK BIM Level 2 mandate in 2016 (ICE, 2016). This, in essence, forced industry to use BIM and BIM models contractually, for any government-funded project and made the industry care about implementing BIM.

Despite many years attempting to use BIM to handle data better, we are not there yet: the industry is still experiencing problems with errors as well as incomplete data from other design parties, poor information exchange between parties, and incompatible software causing problems in transferring information. BIM is not yet delivering the potential improvements in profitability, speed of delivery or reduced cost overruns on projects (ICE, 2019a). Improved collaboration between parties would improve this, whether this takes the form of 'informal' collaboration within a project, or a move towards more enterprise-type business models such as Project 13.

3.9.2 Growing client focus on whole-life value

Underpinning the effort to use BIM is the acceptance that choosing the cheapest build option may prove to be poor value, if taking a whole-life value approach. This is a key consideration for future engineers. By better understanding the purpose of the asset and the needs of society for infrastructure, and people's perceptions and social outcomes, we can get better value overall (Bew, 2017). The UK Government is urging the industry to move away from 'design' and 'build' in the future, and to apply new and better processes and technologies that also support 'operate' and 'integrate' – with digital twin and systems thinking especially (ICE, 2019b)

BIM thinking has now developed into detail about creating a digital twin of a built asset – a digital representation of a physical asset that is also connected to its physical twin to exchange real-time data. The focus is less on saving during construction, and more on saving from more efficient running of the asset.

There is also a move to link up these digital twins, at least for transport, energy, water and telecommunications. These connected digital twin models could vastly improve how infrastructure is managed, maintained and planned in the future. This framework is outlined in the Gemini principles (ICE, 2019c) in which key roles are management, maintenance and planning.

3.10 Lifelong learning for staff

According to Deloitte's report The Fourth Industrial Revolution - At the intersection of readiness and responsibility, which surveyed 2,000 senior executives across 19 countries, business leaders accept that they need to encourage a lifelong learning approach for their staff, to adapt to future needs. Social responsibility is also becoming more important and there is a common expectation that climate change will start having negative impacts. There is a clearer focus on strategy than before, particularly strategy to allow broader adoption of transformational technologies (Deloitte, 2020).

This is echoed by Mace's report, Moving to Industry 4.0, which identifies the known problem of the construction industry's poor productivity levels (Mace, 2017). This report argues very strongly that digital technologies, and especially Industry 4.0, will transform construction, and that the training and upskilling available to construction staff needs to be improved and made available on a lifelong basis. It predicts that more than 600,000 construction employees will need to be reskilled with the new digital versions of their traditional trades, as well as "non-construction technical, professional, IT, and other office-based staff" (Mace, 2017, p. 7) over the next two decades. The Mace report also suggests that these are "jobs the construction sector may wish to train in", which shows sensitivity to the fact that some construction workers may find this a very challenging change of role.

McKinsey's The digital future of work: What skills will be needed? is a video that includes interviews with experts who agree that lifelong learning is a certainty, and not much else is certain about the life of work facing new entrants to the workforce. However, creativity and analytics are likely to be highly useful as they are adaptable skills.

3.11 How to adjust? Start small

Intel's Automation Alley 2019 Technology in Industry report contains various case studies (Alley, 2019). The advice is that Industry 4.0 requires organisational changes to be made, but that companies need only start with small steps. For example, an agricultural machines manufacturer has improved the precision and quality of the 'marriage' stage of manufacturing (i.e. when the bodywork is connected to the chassis) so time-wasting reworking no longer occurs. Another example is a car parts manufacturer that improved its goods-in process through the use of radio frequency identification (RFID) technology to automate counting controls and warehousing.

Both of these firms required "only modest capital expenditure" for these new technologies, notes the report. Although the impact of these changes was not as great as could be achieved, they demonstrate that it is possible and worthwhile to "start small". However, the corollary of this is that the engineering industry could face significant competition from firms using Industry 4.0 techniques that are currently more efficient than construction firms.

PwC recognises that most companies are nowhere near being digital champions, based on surveying more than 1,100 executives at global manufacturing companies (Global Digital Operations Study 2018 – Digital Champions). Industry 4.0 encompasses end-to-end digitisation and data integration of the value chain, and Asia is leading the way. The best 'digital champions' are managing to create value through integrating operations, technology and people to serve customers with competitive, integrated end-to-end solutions.

3.12 Digitisation hype and policy

In Industry 4.0: Building the digital enterprise, PwC found that digitisation came with a lot of hype but still drove leaps in performance. Digitisation can deepen relationships and understanding with customers, but the shift needs to be a culture change, and built using good data analytics and digital trust to avoid breaches and maintain data integrity. This means ensuring there is good data security and transparent processes is essential. Most companies are not currently set up well to support data analytics as an enterprise-level capability, and large investment is needed (a figure of investment of ~5% p.a. of annual revenue is mentioned (PwC, 2016) (Reinhard Geissbauer J. V., 2016)). This suggests that civil engineering may need a change of culture into 'digital thinking'.

In Engineering priorities for our future economy and society (RAE, 2019), the Royal Academy of Engineering sets out the priorities for upcoming policy and spending decisions in the UK. Its digital policy champions the establishment of world-class digital connectivity and infrastructure. The academy also says that cybersecurity is a priority that should receive funding, as a prerequisite, for new digital technologies. It also wants a more diverse workforce, so suggests making computing courses appealing to a wider range of young people in school (women only make up 15% of the technology workforce), warning that if the skills gap is not addressed, £141bn of growth in the next decade will be unrealised.

In his presidential address, ICE President Paul Sheffield said big data was starting to show us the way digitisation could help and where the biggest efficiency gains could be made in building management. Creating a digital twin of existing infrastructure is a starting point to this being done more widely. Helsinki is leading the way in capturing smart data from its entire building estate. It is incumbent on civil engineers to ensure their digital twins are universally intelligible to other models, so that every asset owner's model can integrate with every other (as championed by the Centre for Digital Built Britain) (Sheffield, 2020). What does the ICE need to do to lead on this?

The Transport Infrastructure Efficiency Strategy (TIES) is the UK Government's effort to get the main transport bodies to work together and harness the spending power of publicly funded transport infrastructure to improve productivity and drive efficiency and generally help the UK economy (DfT, 2017). The strategy emphasises that, by improving the way projects are set up – with clear objectives, defined sponsor remits, defined delivery structures and clear governance – the consistency needed between projects, companies, and the industry as a whole can be achieved. Using whole-life cost information is the only way to make more effective decisions. By standardising assets, and asset information, digital technologies can be fully exploited. Industry must innovate, invest and upskill to boost productivity, and offsite construction is a great way to improve efficiency across construction (DfT, 2017).

4 SUSTAINABILITY AND NET ZERO

This section will focus on five key topics in sustainability: the importance of sustainability and net zero for engineering; future skills and knowledge for sustainability; material use; sustainable development; and net zero.

4.1 The importance of sustainability and net zero for engineering

The importance of sustainability and net zero for the future civil engineer has been considered by many authors and can be first demonstrated by results of various surveys undertaken in the past year. AECOM's The Future of Infrastructure study has heard the voices of 10,000 citizens from 10 major cities and found two stand-out priorities for residents: upgrading public transportation and enhancing environmental sustainability. The results show that almost half of respondents (45% overall, and 64% in Hong Kong) "believe other city governments are doing a better job than their own in fostering environmentally sustainable practices" (p. 36, Sydney edition).

Furthermore, the National Infrastructure Commission's 2020 study includes findings on 'future resilience'. These centre around climate change as a developing challenge for infrastructure. Indeed, future civil engineers will need to step up to both public and industry desires for sustainable and low (or no) carbon solutions. This is critical and will need sufficient investment.

4.2 Future skills and knowledge for sustainability

In a special issue of The Structural Engineer entitled 2040 Vision, authors consider the skills of the future structural engineer. In the foreword by Clark and Ibell (IStructE, 2020), it is noted that we are entering an era of opportunity or innovative engineering, where these skills are required in "responding to the acute embodied-carbon issues associated with our climate emergency". The essential cultural changes require engineers (structural, in this case) to embrace disruption, and learn new skills, attitudes and talents, and nurture these in future engineers. Other papers in 2040 Vision urge us to value "empathy, creativity and collaboration skills, as much as our technical capability". For example, Bell (2020) outlines seven future structural engineering archetypes that will fulfil the need for diverse backgrounds and skills in engineering, who can then work together to achieve great things. These archetypes are:

- Project leader – the person who defines what is to be done, why, and inspires everyone to do it.
- Sage – the consultative adviser to project stakeholders, able to integrate technical and non-technical information and needs, lateral functional thinking and vertical in-depth thinking, and embracing uncertainty, to make effective decisions.
- Designer – strong and instinctive understanding of structure behaviour and performance, responsible for design safety and understanding contributions of other professions.

- Niche expert – someone with specialised expertise e.g. structure types or hazards and loading – may be within or outside the firm.
- Digital simulator – expert in numerical modelling of a broad range of physical phenomena, responsible for creating sophisticated digital models.
- Inventor – part researcher, part practitioner, part entrepreneur.
- Societal leader – an engineer who helpsto define and solve the problems of the day, and champions them with the public and via policy.

Also in this issue, McGilveray and Pierce (2020) recognise that the future of specialisation depends on an "introduction of a generalist engineering figure in the design team to complement the skills of the architect in a more holistic manner" (p. 20). They suggest that consulting structural engineers would be perfectly suited to this role of a specialist generalist figure: see sections 5.1, 5.2.6, and 6.2.1 for more detailed explanations of this role.

The final paper from 2040 Vision for consideration is de Hoog (2020), who recognises that future civil engineers must be human-centred, thinking more creatively and about human need. Understanding that engineers will need more hours in the day, she offers technology as a time-saving solution, and also floats the idea of engineering degrees being a year longer to incorporate more critical, creative and artistic skills. Oswald Beiler and Evans (2015) go further on this point, suggesting that sustainability topics in engineering should be taught at secondary school level.

In addition, Lathem, Neumann and Hayden (2013) assessed civil and environmental engineering students' attitudes to changes in their curriculum that included sustainability, systems thinking and social responsibility. They found that the changes did not affect students' self-reported sense of technical knowledge and social responsibilities overall: however, a positive statistically significant difference was seen in female students.

As a final point on future skills, Rogers (2018) recognises that the future civil engineer must seek to "enhance social, environmental and cultural benefits from designs that are almost always constrained by economic considerations – and thereby conform to the principles of sustainability, resilience and liveability" (p. 7). He offers three scenario-based methods for civil engineers to determine the value of future infrastructure schemes: the 'Designing Resilient Cities' method; the 'Liveable Cities' aspirational futures method; and the 'iBUILD' method (see section 6 on foresighting methods below).

4.3 Material use

Fivet and Brutting (2020) highlight the (re)emergence of reusing structural components over multiple service lives and in new layouts, a circular economy strategy which utilises a given stock of reclaimed components. While this proves positive for sustainability agendas, there is a lack of expertise, tools, technology and metrics. They note that future civil engineers will need to help define metrics and benchmarks around reused materials.

Ronalds (2020) offers a personal perspective on future material use and argues that the broadening range of materials on offer poses both opportunities and challenges for future civil engineers. He argues that the logical approach to navigating the increase in options will be for engineers either to specialise in detail on one particular type of new material (e.g. carbon-fibre reinforced polymer) or to be materials generalists who can understand how different materials are likely to interact.

He does caveat this, however, by acknowledging the need for a holistic view concept design stage of a project, as particular materials may not have been chosen from the outset. It is through a balance of generalists and specialists that future civil engineers will "make greater headway in developing new materials, make better use of our existing building stock, design better buildings and make quicker progress towards meeting the [institution's] climate declaration" (p. 60).

In Moynihan's (2020) piece on ending the 'bog standard' of new build, it is suggested that engineers rethink how they approach their roles in society. For him, the focus is on reducing the use of steel and cement, as their combined production accounts for about 10% of global CO2 emissions (or 4,400m tonnes of CO2 annually). Future civil engineers must upskill themselves in this area, moving away from delivering in the same way as before. Moynihan lists four main strategies to reduce the use of these materials, while still meeting the needs and demands of society:

- specify sparingly
- adopt alternative materials and methods
- reuse and refurbish and
- build in resilience to deliver long-life structures

In ASCE's guide, Future World Vision: Infrastructure Reimagined (ASCE, 2019), it is suggested that 3D printing may play a larger role in future construction, allowing new materials to be placed at the forefront. Materials such as self-healing concrete could help to build more sustainable and resilient communities (Shuster, 2019).

A similar bold and ambitious vision is championed by Chris Wise (2012), who calls on the building industry to run more experimental programmes on everyday construction types, testing and learning from performance first. He envisions Nissan's Delta Wing experimental racing car as an inspiration for this type of thinking. Nissan claims this car has half the aerodynamic drag, half the tyre wear, uses half the fuel of other racing cars, and can reach up to 190mph with a 1.6-litre engine. Interestingly, an article in the 'Raconteur' Future of Engineering series (2018) by Prof Steve Evans also looks towards Nissan as an inspiration, claiming the car firm has "written the book on resource efficiency" (p. 11), owing to their 8% year-on-year resource productivity gains.

4.4 Sustainable development

Many argue that the engineer of the future recognises their global responsibility to sustainable development. The RAE's 2016 report Engineering a Better World: Achieving the United Nations Sustainable Development Goals demonstrates the contribution that engineering has in tackling some of the world's biggest problems, in the framework of the SDGs. An example given here is an ongoing Mott MacDonald project, Blue Gold, which aims to alleviate poverty for 150,000 families in Bangladesh. The project is working to enable communities to lead in identifying, implementing and maintaining solutions. This in turn allows local people to become self-sufficient when financial assistance ends.

This RAE report goes on to highlight the work engineers are doing globally in each of the 17 SDG areas, such as harnessing data to deliver water and sanitation for all and combining engineering solutions with policy change to cut plastic pollution. It is a demonstration of the incredible breadth of areas that engineering covers, and the impact it should continue to have in the future with the help of new generations of engineers. Civil engineers will contribute to the fulfilment of the SDGs in the future.

In ASCE's third edition of Civil Engineering Body of Knowledge: Preparing the Future Civil Engineer (ASCE 2019c), it recognises that sustainability is one of its technical outcomes. Some key factors future civil engineers will need to consider are a systems approach to projects; building resilient infrastructure; and recycling and reuse of materials and resources. ASCE recognises here that the future civil engineer will be "expected to be proficient in the application and analysis of principles of sustainability in all design work they perform", and be able to holistically analyse the sustainable performance of complex projects, considering the environmental, economic and social factors at project and systems level.

ASCE predicts these outcomes being achieved through both cognitive and affective domains. For the cognitive domain, fulfilment of outcomes is expected through both undergraduate education and mentored experience. For the affective domain, this sustainability outcome can be fulfilled through a combination of undergraduate education, mentored experience, and self-development.

ASCE's 2007 publication, The Vision for Civil Engineering in 2025, is also relevant. This sets out what the ASCE believed in 2007, and what would be different in the world of 2025, and the part civil engineers would be playing. They developed a scenario using Summit results and a member survey, which features predictions such as "the profession has led world acceptance of green design and has been at the forefront in making environmental considerations part of life-cycle and cost-benefit analyses", and "new processes, less harmful to the environment, have been implemented, and most new construction is based on green and smart-building technologies" (p. 14). It is even suggested that by 2025, many new buildings would produce more energy than they consume.

Susan Krumdieck's recent book, Transition Engineering – Building a Sustainable Future, identifies types of obstacles that have hitherto prevented progress on engineering projects with sustainability objectives. In addition to the fundamental "mega-problems of unsustainability" (e.g. exponential growth, reliance on the consumption of fossil fuels), she also identifies a misunderstanding of complexity and poor communication as particular difficulties. She proposes three 'transition engineering concepts' to correct some of these mistakes (e.g. "Wanting a good thing to happen is not an effective way to stop a bad thing" (p. 9); "Global average temperature of two degrees is not a target, it is a failure limit" (p. 16)), and then expounds her 'transition engineering' method in detail in the remaining chapters.

4.5 Net zero

The issue of net zero carbon dioxide emissions has become increasingly important. One of the papers in 2040 Vision (Cook, IStructE, 2020) reminds us that buildings and construction account for nearly 40% of energy-related carbon dioxide, highlighting how engineers are to play a major part in the climate emergency. Cook notes that this footprint is primarily down to the materials needed to build and maintain buildings, fuels to heat them, and the destruction of green land to create new sites.

Considering these factors, and recognising that 90% of the world's current energy supply is from fossil hydrocarbons and therefore produces CO2, Krumdieck (2020) proposes the concept of 'shift projects', and an accompanying method of transition engineering. Shift projects aim to change "existing complex systems to radically lower energy and material use while preserving essential functions". For her, this energy transition is the only way to mitigate climate change. Future civil engineers may find themselves falling under this category of 'transition engineers', carrying out projects that develop resilience and adaptive capacity, and achieve long-term environmental, social, economic and cultural well-being. Krumdieck notes how "all successful transition engineering projects will improve the competitive position of the organisation now, each year through the payback period, and beyond the project lifetime".

The majority of Krumdieck's book (p. 79-215) is devoted to explaining how the 'transition engineering' method enables civil engineers to achieve demanding sustainability targets, such as net zero. The method comprises seven stages:

1. Study the history of the project, "the existing activity system of a group of people in a specific place" (p. 80).
2. Take stock and identify the specific features of the current situation.
3. Develop and explore future scenarios and then apply insights from these to the 'Forward Operating Environment', which explicitly includes demanding constraints such as net zero that must be achieved.
4. Use 'time travel' to brainstorm these ideas further.
5. 'Backcast and trigger' (p. 110) i.e. develop a clear picture of how what actually is differs from what is needed, and the triggers that enabled the change in stages (3) and (4).
6. Design the 'downshift project' using all the insights gained.
7. Investigate transition management scenarios for the downshift project, including how the shift in direction (e.g. to net zero) also leads to "new businesses, social benefits, and environmental regulation" (p. 81).

She also devotes a chapter each to the topics of 'Economic decision support' and 'Transition economics: balancing costs and benefits' to provide further assistance in making very demanding targets real.

The NIC's plan of action for the country's infrastructure over the next 10 to 30 years (found in the National Infrastructure Assessment, 2018) is also interesting from the carbon perspective. One of the key recommendations for the UK's economic infrastructure is that half of the UK's power should be provided by renewables by 2030. This will make a big dent in carbon emissions and influence the impact of future civil engineering. In the chapter Low Cost, Low Carbon, the report describes how the UK can achieve low cost and low carbon electricity, heat and waste. It also suggests a key step for future civil engineers is to improve the energy efficiency of the UK's buildings.

It is also important to recognise the potential for offsite methods of construction to drive efficiency and reduce carbon (Campbell, Cooper and Waugh, 2020). Offsite methods will change the type of projects that civil engineers work on when improving existing infrastructure or creating new renewable energy sites.

Others argue that the future will bring new ways of understanding value and cost. The ACE's reports Future of Consultancy Overview (2019a) and Future of Consultancy - value based business models (2019b) both set out five ways to measure value, two of which might be traditionally classed as part of sustainability: natural (environmental) capital and social capital. It also notes that a driver of change is the "increasing influence of ethical investors: 50% have increased their allocation to sustainable funds compared with five years ago" (p. 2).

Similarly, in the government's National Infrastructure Delivery Plan 2016-2021 (IPA, 2016), it is stated that a priority for this five-year period is "incentivising lower cost, lower carbon solutions". The plan recognises a "clear link between reducing carbon and reducing cost", and notes that management of carbon in infrastructure must be matured rapidly. It is suggested in the plan that this will be achieved by implementing rules and guidance, namely PAS 2080, which shows "how carbon in infrastructure can be managed more rationally and strategically" (p.100). Carbon reduction is becoming increasingly important, and will be an essential skill for future civil engineers.

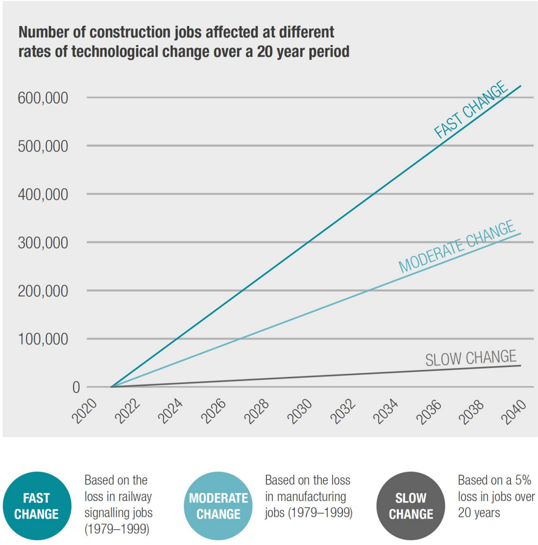
5 PRODUCTIVITY

Productivity in engineering has many different aspects: the coordination of different people and professionals around a common objective on shared tasks; the use of different types of machinery often pushing at the limits of what it can achieve technically and safely; the production of designs that minimise the use of materials, energy, people, and costs; and the fabrication of parts, whether standardised designs or bespoke. But construction has a poor reputation for productivity. This section discusses the scale of the UK's productivity problems, the causes and solutions

5.1 The scale of the UK's productivity problem in construction

When compared with other sectors and countries, the scale of the UK's productivity problem in the construction industry is stark. Over the past decade, output per worker in manufacturing grew by 50% and there has been growth of 30% in the services sector. Output per worker in construction, by contrast, has remained flat (Mace 2017, p. 3). The graph opposite shows this under three different rates of technological change (taken from Mace, 2017, p.11).

Similarly, measured by gross value added (GVA), whereas the UK economy in its entirety produces £31.50 of GVA per hour worked, construction manages just £25.50 of GVA per hour worked (Mace 2017, p. 2). Therefore, construction is not just lagging behind high growth sectors in productivity, it is significantly underperforming when compared with the UK economy as a whole.



International comparisons of productivity are similarly concerning. Average productivity in the UK economy is low compared with peer group countries like France and Germany and it has been claimed that the average worker in France can achieve the same output as a UK worker by Thursday afternoon (IMechE, 2016, p. 4). Yet, although the UK is undoubtedly underperforming, low growth construction is a problem for the developed world as a whole and it is expected that through 2030, annual construction growth in the developed world will be just half that of the world average (ACE 2019b, p. 11).

This section will focus on factors within the construction and related sectors. Although demographic and policy factors are important, too, they are beyond the current scope of this literature review.

Causing the productivity problem are: inadequate design processes; poor project management; insufficiently skilled labour; and underinvestment in digitisation, innovation and capital (Mace 2017, p. 4). Concern has also been raised about the increasing specialisation within the construction process which, despite having a positive impact on certain efficiencies and quality, has also caused fragmentation and 'silos of knowledge' to develop which inhibits the development of 'coherent, holistic design' (McGilveray and Pierce 2020, p. 20).

5.2 How can we solve the productivity problem?

5.2.1 Innovation and research and development

Within the construction industry, there is extensive evidence and acknowledgement of the fact that greater standardisation and pre-assembly can "drive innovation, improve productivity and reduce waste" (DfT 2017, p. 64). Already, offsite construction is generating significant productivity gains. For instance, using 55% offsite building components on the Western General Hospital in Edinburgh has produced a 20% reduction in project duration (RAE 2019, p. 5).

As the industry embraces the move to offsite working, further innovation in construction will be spawned. Many authors argue that the extent of technological unemployment in the construction sector will be highly significant with a very large majority of current workers becoming unemployed (e.g. RAE 2019; Mace 2017). The RAE report envisages that such unemployment will be so pervasive – even with high-quality upskilling – that the whole basis of national taxation and welfare provision may need to be rethought (RAE 2019, p. 9; see also McKinsey, 2018).

Even a recent McKinsey report that seeks to downplay the scale of technological unemployment (Automation and the future of work, McKinsey, 2018) still recognises that the jobs most vulnerable to automation in the next 10 to 15 years are "routinised physical activity in a predictable setting" (which describes at least part of the current construction skill set) and "collecting and processing data", and that 375 million workers worldwide will need to shift roles by 2030. The job loss projections reported by Mace (2017) for the construction trade specifically, under conditions of fast technological change, are of an average 94% loss in numbers of workers required across 10 different construction trades.

Although innovation is vital in improving productivity, it is not a quick fix. For instance, in IMechE's report, Industry 4.0: transforming agility and productivity, the CEO of Siemens plc estimated in 2016 that full automation and data analysis could make factories up to 50% more efficient in terms of productivity, but that this transformation would take 10 years to implement. This illustrates the need for a long-term strategy to enable potential productivity gains to be achieved.

For every £1 spent by the government on R&D, private sector R&D output rises by 20p a year in perpetuity, by raising the level of the UK's knowledge base (RAE 2019, p. 3). Therefore increased investment in R&D will help to increase productivity. This report, Engineering priorities for our future economy and society, is focused on the UK engineering sector as a whole; however, it does make a few recommendations relevant to infrastructure and civil engineering. One is that overseas projects that fall under the remit of the Official Development Assistance programme (designed to foster partnerships between innovative UK organisations and low-to-middle income economies) should include the UN SDGs as part of each project's objectives (p. 3). The second recommends improvements in existing infrastructure systems without specifying whether this should be only for new or improved infrastructure.

Integrated strategies for "transport, employment, and housing" are specifically mentioned, as is the need for integrated transport (air, rail, and road). Government reports echo this call for improving existing infrastructure. For instance, by improving existing transport infrastructure (e.g. Highways England standardising road assets) and creating more infrastructure (e.g. Crossrail) to meet growing demand, productivity of the transport infrastructure supply chain and construction can be improved (DfT 2017, p. 15), because a steady stream of infrastructure work means more opportunity to refine processes to improve productivity.

5.2.2 Offsite manufacture

Bowkett et al (IStructE, 2020) vividly show that productivity can be dramatically enhanced by experimenting with novel construction techniques. For example, Mace used a technique nicknamed 'the jump factory' in the construction of two high-rise buildings. "The basic premise was to build a fully functioning factory, use the factory to construct a floor of the building [using modular and prefabricated elements], then once the floor was completed on a weekly cycle, jack the factory up and start again" on the floor above (Bowkett at al. IStructE, 2020, p. 50). This provided an improvement of two to three days (approximately 30%) on the standard construction time of similar projects.

Furthermore, as the 'factory' was strengthened and enclosed, work was not delayed by high winds or wet weather (p. 54). See section 5.2.1 above for a description of an extension to an existing hospital in operation where prefabrication methods significantly improved productivity. As the article concludes, it is "only by trialling new methods of construction [that we will] be able to capitalise on historic lessons learned and help define the future of the industry" (p. 55). Over time, civil engineers may be able to improve these efficiencies further.

5.2.3 Industry 4.0 as a possible solution

Much of today's innovation in construction is grouped under the broad heading of Industry 4.0, which encompasses the "automation of manufacturing, machine-to-machine and machine-to-product communication, the industrial internet and technology" (IStructE 2020, p. 2). Many large UK construction companies have developed comprehensive, long-term strategies for the incorporation of Industry 4.0 into their business and early evidence suggests this quickly generates higher growth (Deloitte 2020, p. 3, 6). Some 80% of high-growth companies have dedicated teams focused on innovation (p. 18).

Gains in productivity from the use of new technology have the potential to transform the industry: for example, the Rapid Engineering Model (REM) is being used by Highways England for motorway design, reducing the task from months to weeks (DfT 2019, p. 27), while Building Information Modelling (BIM) is used to generate accurate 3D views, enabling the first phase of a 450-unit apartment block to be completed in less than seven months rather than 13 (ACE 2019a, p. 8). By persistently investing in R&D, firms have higher productivity, better value added per employee and higher exports (BIS 2014, p. 7). However, the specific ways this will affect the future civil engineer will depend on the interaction of the factors described in this literature review. The use of REM and BIM models is an emerging new role for civil engineers whose importance will continue to grow.

5.2.4 Skills and training

To take full advantage of the opportunities offered by Industry 4.0, employers and employees need to be both knowledgeable about, and skilled in, the new technologies available. Although progress has been made, a majority of firms have identified clear skills gaps in a number of areas as well as uncertainty surrounding new technologies (Mace 2017, p. 8). One approach to counteract this is for employers to take an active approach in identifying skills gaps and arranging in-house training rather than leaving it up to the individual employee to proactively pursue (Deloitte 2020, p. 11). However, given the pace and scale of technological change in the infrastructure sector, a more effective approach is for employees to upskill each other. The Siemens case study (below, section 8.1) shows how digital training for practitioners by practitioners (rather than by dedicated training professionals) can be extremely effective and is becoming more important: consequently, the ability to identify skills gaps and train colleagues in new technologies could become an important part of the civil engineer's skill set.

The scale of retraining necessitated by Industry 4.0 could mean up to 600,000 people needing to be reskilled in the construction sector alone (Mace 2017, p. 12). Major steps are required for this to be feasibly managed, such as: accelerating the use of technology in training, identifying skills gaps and providing the right training to address them, and ensuring that post-16 education equips young people with the relevant knowledge for 21st-century construction. The RAE recommends that comprehensive retraining be made available for all, including support in finding new career opportunities as technologies change (RAE 2018).

5.2.5 Expanding the pool of talent to increase productivity

Another factor affecting productivity is the reliance on people from a somewhat narrowly defined educational background. Since innovation requires the effective combination of insights in new ways, a more diverse recruitment base should enhance productivity. Therefore, several authors have argued for the need to increase the educational, ethnic and cultural diversity of engineering students, apprentices and employees (e.g. NCUB, RAE, Perkins). Rather than focusing almost wholly on those who studied STEM subjects at school, it is important that the arts and humanities are brought into mainstream engineering, because future engineering may also require the use of social and emotional intelligence.

By diversifying its knowledge base and skill set, engineering can not only enhance its impact on the world, but could also improve its productivity. Evidence of this can already be seen by innovative business models within engineering frequently coming from outside the industry (de Hoog, IStructE, 2020, p.18; RAE 2016, RAE 2018).

By attracting people without traditional STEM skills (when STEM background applicants have not been increasing as previously hoped), but attracting people with, say, digital skills acquired and used in other sectors, creates a larger talent pool. This would also increase the diversity of experience and knowledge within engineering. The National Centre for Universities and Business (NCUB) says: "The supply of STEM and digital skills via schools is not meeting rising demand. More focus is needed on retraining staff to encourage intersectoral mobility, transferring skills within the engineering sector and meeting the challenge of recruiting talent from outside engineering" (NCUB 2019, p. 6).

5.2.6 'Generalist' roles and perspectives

Although new technologies are often touted as a guaranteed way to increase productivity, one unexpected consequence of implementing new technologies – especially at a time of very rapid technological change – is that different technologies work in slightly different ways that don't always 'match up'. McGilveray and Pierce (IStructE, 2020) argue that this is an increasing productivity problem in engineering. Identifying the causes of such mismatches, and devising solutions, requires engineers with specialist skills in multiple technologies and synthesising skills so that the performance of technology can be effectively coordinated.

McGilveray and Pierce propose the new engineering role of 'specialist-generalist technical lead' who would have as important a role as the existing design, commercial and construction leads. They claim that such a model would create "more informed, holistic and streamlined" decision-making, thus improving productivity. This type of role would be in addition to existing roles which may be more specialist or generalist in character. However, this specialist-generalist role would need investment in learning about the trade and techniques of other professionals within the construction industry.

Recognising the same productivity challenge, Shuster also suggests that a new type of civil engineer is needed, who is "expert at data analysis, adept at collaborating and coordinating with other professionals and an ability to integrate systems together…" (Shuster 2019, p. 63). Working across disciplines in a generalist role has echoes of new commercial models for construction projects and, in particular, Project 13. DfT states that this approach will support the supply chain "to accelerate its own restructuring and boost productivity" (DfT 2017, p. 49).

Project 13 establishes new roles for those involved in a project, changing client and contractor direct relationships to an integrated team approach involving owners, integrators, advisers and suppliers. The suppliers and advisers are experts in their subject area and they are accountable for the delivery of specific aspects (Brown 2018) but the ultimate focus is on working collaboratively with others to solve shared problems so that project outcomes are achieved.

5.2.7 Soft skills

Multidisciplinary and multi-organisational teams have become standard practice on complex projects. The ICE Professional Skills report identified this as being a major reason why soft skills will become a more integral part of civil engineering work (ICE 2018, p. 31). This is a common theme in engineering. As the sophistication and capacity of AI develops, many tasks which engineers once completed manually will become automated. Fischer consequently argues that it could be "how expertise is delivered, and to whom, that will become the real source of premiums in the expertise business". AI will put into sharp relief the value and necessity of the innately human characteristics of "judgment, intuition, creativity, empathy and values" in the commercial domain (Fischer 2015).

Similarly, de Hoog argues that the ability to feel, think creatively and interact personally are the traits least replicable by technology and therefore the ones engineers should focus on for future development (de Hoog, IStructE, 2020, p. 17). These will be key attributes and skills for the future civil engineer.

6 FORESIGHTING METHODS

In her recent book Transition Engineering, Susan Krumdieck provides a brief overview of 'futuring methods' in civil engineering, also called 'foresighting' or 'using scenarios'. She notes that although there have been many different methodologies for creating scenarios developed since the 1980s, civil engineers have very rarely used them. This is despite the fact that some (non-civil-engineers) have developed scenarios including "engineered systems and technology" (p. 94). Although there can be methodological concerns about the ways scenarios are developed – there is no standard methodology; the usual process is "storying telling based on a set of assumptions, producing an if-then narrative" (p. 94); scenarios tend to give results consistent with the preferences of funders – she still sees them as a very useful part of the transition engineers' toolkit. (See section 4.5 for a summary of how her InTIME method uses scenarios.)

Rather than be an exhaustive review of foresighting methods per se, this section summarises the two relevant papers identified in the initial literature search for the present review. These relate to foresighting for civil engineering in general rather than for particular infrastructure types (e.g. transport, water).

6.1 Foresighting methods

Some authors have recommended foresighting methods as a way to enhance civil engineers' systems thinking skills.

6.1.1 Rogers (2018)

Rogers (2018) begins by noting that although systems thinking is something for which all engineers strive, there are no replicable methods that will guarantee that engineers will not tend towards siloed thinking. Although siloed thinking is always a risk, Rogers argues that scenarios thinking can help to reduce that risk. Not only is systems thinking very difficult, but civil engineers are often constrained in their thinking by their assumptions about current business models.

To address this challenge, he recommends the use of scenarios to help engineers 'map the systems' of the project they work on, so that they map the dependencies and interdependencies more comprehensively than is typical at present. The systems maps that result should not be seen as providing a single 'solution', but as a tool to help create ideas, enable more informed and broader thinking to inform decision-making, and a greater awareness of issues that may arise with others during implementation.

His method is distinctive because it combines three previously established scenario methodologies: Designing Resilient Cities; Liveable Cities; and iBUILD. Each of these methods focuses on different aspects of a future scenario. ‘Designing Resilient Cities’ focuses on four different types of “extreme yet plausible” scenarios (market forces; fortress world; policy reform; new sustainability paradigm); Liveable Cities focuses on aspirational aspects of the future and iBUILD on alternative business models that are needed to generate investment for future scenarios.

Reid then uses this combined method to focus on five key objectives: sustainability, resilience, adaptability, liveability, and ‘smartness’ (i.e. extent of digital technology) and produce scenarios to help engineers understand how different factors may interact. Therefore, scenario-based thinking could be a very useful future planning method for civil engineers.

6.1.2 Shuster (2019)

Shuster (2019) argues that civil engineers will need to be systems integrators to manage infrastructure in future, and especially to understand how six key future factors will interact: climate change; alternative energy (solar or, optimistically perhaps, fusion); high-tech construction; automatic vehicles; smart cities; and changes to funding. Scenarios will help engineers to understand how these future factors might interact.

Shuster outlines four scenarios: Resilient Cities; Progressive Megacities; Dispersed Settlements; and Unequal Enclaves. Each of these shows distinctive interactions between different infrastructure systems, funding types, governance and new technologies. For instance, Resilient Cities use new building materials and construction methods. This is initially challenging to achieve because it has higher upfront costs and engineers need to be skilful persuaders of all stakeholders of the benefits of the new materials and higher costs, but the persuasive work of engineers has benefits later in enabling collaborative research into carbon sequestration, negative emissions technology, and alternative energy.

Unequal Enclaves is a scenario in which governments have become unable to support new infrastructure systems for AV, energy, and flooding defence, which affect everyone. Consequently, the wealthy live in enclaves where private energy, AV, and flood defence systems have been developed, while poorer enclaves struggle to provide or maintain infrastructure (including smart systems). In this scenario, Shuster argues that one of the tasks of civil engineers is being an advocate for society-wide infrastructure systems, and to collaborate with both city planners, cybersecurity experts, climate risk experts and robotics designers to achieve this.

The above are both scenarios in which the majority of the population is still expected to live in cities, but other scenarios are also valuable tools to use to understand how to integrate across systems. Dispersed Settlements is a scenario in which solar panels are the main energy source, accompanied by commercialised energy storage. As a result of the decay of urban life, and the availability of massively localised energy production and storage systems, people have moved out of cities if they can. The focus of civil engineers in this context is on smaller, more isolated ‘mini-cities’, for which strong cybersecurity is necessary, trying to make each individual settlement as resilient as possible.

Taken together, these scenarios reveal how different the effects of the same technology in different circumstances can be, and how civil engineers will need to use different skills in them to enable the best infrastructure outcomes for society. Key to this is the engineer’s ability to integrate understanding across multiple systems – a skill that Shuster believes cannot be automated. This will be a key skill for the future civil engineer.

7 INTERACTIONS BETWEEN FACTORS – MOVING TOWARDS SYSTEMS THINKING

Please note: the most recent Problem Statement defines this as "interactions between factors – moving towards systems level thinking for asset networks". However, only three reports from two (highly influential) authors in our literature review focused explicitly on this issue (IPA, NIC). Therefore this section also reports slightly wider on 'systems thinking'. This section will define systems thinking; summarise those authors who recommend systems thinking for both asset networks and other contexts; and describe the foresighting methods that have been proposed to help civil engineers with systems thinking.

7.1 Definitions of systems thinking

According to the RAE report Thinking like an engineer, systems thinking is "seeing whole systems and parts and how they connect, pattern-sniffing, recognising interdependencies, synthesising" (p. 48). The RAE also refers to the definition of the National Academy of Engineering: "equipping students to recognise essential interconnections in the technological world and to appreciate that systems may have unexpected effects that cannot be predicted from the behaviour of individual subsystems" (p. 23). Systems thinking is seen to be the opposite of analysis, and akin to synthesis. For three examples of systems thinking in action in the civil engineering context, see the ICE blog Are highways engineers really drainage specialists in disguise? which provides examples from the UK, the Netherlands and China.

In addition to defining systems thinking, Thinking like an engineer also identifies systems thinking as one of six core Engineering Habits of Mind (EHoM), and the EHoM that is jointly most evident (with 'visualising') in current engineers. Futhermore, this EHoM will continue to be the one which is most in demand in the future (again, jointly with visualising).

However, the RAE also notes some concerns about systems thinking. First, one respondent was concerned that systems thinking may "clash" with creativity. Second, systems thinking was particularly important for the most complex engineering but was "particularly difficult to cultivate". Encouragingly however, one respondent felt that systems thinking was best developed when working on real engineering projects.

In this literature review, the use of the words 'interdependence', 'holistic', 'cross cutting' and 'multidisciplinary', 'overlapping', as well as 'more complex', were taken as evidence of systems thinking provided the substance of the text was consistent with this (i.e. reports discussing overlapping activities of professional organisations or similar were excluded).

7.2 Recommendations for engineers to use systems thinking

7.2.1 For asset networks

Infrastructure and Projects Authority (IPA)
The IPA's report National Infrastructure Delivery Plan 2016-2021 (IPA, 2016) provides brief but exemplary examples of recognising the importance of systems thinking in infrastructure, and how this improves projects. Although it does not use the term 'systems thinking' explicitly, it does discuss interdependence as the ability of two or more infrastructure systems to affect each other's performance. It urges the government to "ensure that planning for interdependencies are effectively considered through investment appraisals" (p. 95).

Its brief case study of the Ebbsfleet development shows how the principle of interdependence can be worked with to improve outcomes. For instance, the design created 'multi-utility corridors' at the outset, recognising that multiple types of infrastructure can use, or require access from, a single physical space. The multi-utility corridors were deliberately "structured to avoid, or drastically reduce, the chances of third party strikes on other utility networks when work is being carried out in the future". In addition, these multi-utility corridors were not only designed with gas, electricity, digital and water networks in mind, but also with the transport system in mind so that any repairs would minimise transport disruption too. The IPA notes that this project also used an understanding of interdependence at the outset to identify areas of vulnerability and potential common failure, via a holistic spatial design of all the utility networks involved. This shows how present and future civil engineers need to work collaboratively to see the bigger picture.

National Infrastructure Commission (NIC)
Two of the NIC's reports reviewed for this literature review referred to the issue of interdependencies, and were therefore included. These are its first report, the National Infrastructure Assessment, and the 'scoping report' for its current focus on resilience. A third report, Smart Power, made partial reference to this issue. Its three other reports included in this review (Connected Future, Strategic Investment and Public Confidence, Data for the Public Good) do not explicitly discuss systems thinking issues.

In the National Infrastructure Assessment (2018), the Commission notes that it had been able to consider the interdependencies between sectors, and recommends that infrastructure design be more integrated, designing for the simultaneous needs of different systems such as housing and urban infrastructure networks, the energy system and expected increases in electric vehicle ownership, and digital connectivity and roads. However, although this report emphasises the need for collaboration and efficient thinking, interactions between factors are not considered beyond this brief mention.

The Smart Power report acknowledges that the electricity system is becoming "more complex", both at the National Grid level as systems operator with responsibility for maintaining supply even with the addition of intermittent renewables, and at the level of distribution networks that need to manage distribution and demand also with the inclusion of renewables at local level and new methods for managing demand. However, it does not explicitly discuss other interdependencies even though systems thinking considerations need to be made for all infrastructure types.

However, the NIC's current work on resilience provides a significant shift in focus, in which interdependencies are understood as a necessary corollary of the focus on resilience. The Resilience Scoping Report (2019) explains in some detail why interdependencies need to be a core part of the project. "To be resilient, we need to move beyond managing individual risks or assets, to thinking about the system as a whole and how the services we all rely on can be sustained and disruptions minimised (i.e. despite unexpected or unwanted interactions between factors)". "It is this type of holistic approach that the Commission is trying to develop through its resilience study… To achieve this, however, we need to think more about the interdependencies between different sectors and do more to manage cross cutting challenges" (p. 3-4, NIC, 2019).

The NIC Resilience Scoping Report also explicitly recognises that this is an emerging area of work for the infrastructure sector. Some organisations (no examples given) have already been exploring interdependence. However, the dominant approach hitherto has been to focus on individual sectors, and this was inherently problematic when needing to identify interdependencies to provide infrastructure resilience. Data and knowledge exchange across infrastructure sectors will be needed to identify the location and type of interdependence-related vulnerabilities. "It is difficult to find examples of holistic and cross-sector approaches to resilience… As well as the absence of a holistic view, there are also a number of cross-cutting resilience challenges which require significant changes to the current approach to address them. These gaps will be the Commission's focus in the next phase of the study."

The NIC's final report on resilience was originally expected for publication in March 2020 but is delayed. NIC's current focus on resilience emphasises that interdependence is a key theme for the future of the civil engineer.

7.2.2 For other purposes

Royal Academy of Engineering (RAE)
The RAE's Automation and the future of work report lists 'systems thinking' as one of several EHoMs needed by all types of engineers in the future, along with communication, creativity, problem-solving, and teamwork, but it does not elaborate further.

Engineering a better world: Achieving the UN's Sustainable Development Goals makes a few mentions of the need for holistic thinking, in a paper devoted to arguing for the need to improve biodiversity and green space in regeneration projects. Two themes are identified as being 'cross cutting': risk and resilience, the role of youth.

Association for Consultancy and Engineering (ACE)
The ACE's overview of new business models asserts that systems thinking needs to become a widespread area of expertise. The ACE relates this purely to improved multi-professional working and improved social outcomes on projects, but does not elaborate further.

American Society of Civil Engineers (ASCE)
In The Vision for Civil Engineering in 2025 (ASCE, 2007), there is a partial recognition of the need for systems thinking but this is not made explicit. For instance, the report asks whether civil engineers will "move further into a systems role?", since they already understand a focus on construction issues alone is insufficient. The focus of civil engineers must be "multi-faceted, multidisciplined, and holistic…civil engineers could be… master holistic visionaries, think and work more holistically on infrastructure… take a systems/holistic view of the environment".

A later article in ASCE's journal (Reid, 2016) is more focused and specific about what systems thinking means for engineers. Reid argues that today, civil engineers have to be an active part of all the conversations with other professionals and stakeholders. For instance, civil engineers should be an integral part of conversations about not just water systems but the overall topic of water provision, and able to communicate effectively in a wide range of different contexts. This requires civil engineers to become proficient not only in technical matters but also in "team, communication, ethical reasoning, societal and global contextual analysis skills, work strategies, familiar with political science, how communities work, how laws are made and regulations established" (p. 65).

Institution of Civil Engineers (ICE)
The ICE Professional Skills Review (2018) recognises that civil engineering work is becoming "more complex, multidisciplinary" but does not focus on this issue. However, a number of other ICE resources have focused explicitly on it. For instance, Blockley and Godfrey have argued for the need for "joined-up systems-thinking for construction professionals" (Blockley & Godfrey, 2017, p. xi) in the first (2000) edition of their book about systems thinking methods, and that systems thinking is now not just required by construction professionals but by "everyone concerned about our infrastructure" (p. xi) in their second.

Institution of Structural Engineers (IStructE)
The January 2020 edition of IStructE journal is entitled 2040 Vision and devoted to 15 articles envisioning the future. Four papers make brief mention of systems thinking concepts, but it is completely neglected in others. For instance, new roles are needed to provide a holistic perspective (McGilvery & Pierce, 2020; Burrows, 2020), and a digital specialist recognises that work is "becoming more complex" (Clipsom, 2020) as is digital manufacturing. However, even papers with titles such as 'An expansive vision of structural engineers' or similar do not address systems thinking as an explicit issue. Systems thinking is something that people are aware of as the future, but perhaps needs more research and thinking into implementation strategies.

8 DIVERSITY

There is universal agreement that the engineering industry must adapt to embrace disruption. Diverse skills such as empathy, creativity and collaboration need to be valued as much as technical capability. A broader outlook is required to be influential in addressing the future challenges that society faces. This section establishes the bold vision for the future, the new engineering archetypes that will be required and how education and training must adapt to attract and nurture the skill sets needed.

8.1 A bold vision

In 2006, top industry leaders came together in an American Society of Civil Engineers (ASCE) summit to develop a global vision for civil engineering in 2025. They also created a profile of the future civil engineer. The results were detailed in the ASCE (2007) Vision for Civil Engineering in 2025 report. This states that in 2025, civil engineers will serve as master builders, environmentalists, stewards, innovators and integrators, managers of risk and uncertainty, and leaders in shaping public policy. It is a vision achieved through a truly global and multicultural profession where everybody learns from one another's experience because new and exciting projects will be in abundance. Adaptability to and respect for different cultures will be valued in a world where global sourcing and multidisciplinary teams are the norm. (Note: a vision conceived in 2006 is quite dated already.)

A common theme in conversations between structural engineer professionals is that a bolder, more expansive vision is required, particularly in defining the roles that engineers undertake (An expansive vision for structural engineers, Bell, IStructE, 2020). Although civil engineers are experts in technical essentials, in structural and material behaviours, in solving problems, in conceptualising and delivering construction projects, Bell states these qualities will not change but should be considered in a much broader context since engineers will also be project as well as societal leaders, collaborators, innovators, value-producing and sage advisers in weighing risk and reward, while using their creative, uniquely human skills.

8.2 Engineering archetypes

Bell argues that the structural engineer of the future would need to be superhuman, having all technical skills and knowledge of the widest possible technical disciplines, as well as possessing comprehensive soft skills such as leadership, communication, creativity and entrepreneurship. Interestingly, the realisation is that a one-size-fits-all approach is neither realistic nor effective. Instead, to achieve best results, the importance is on having a profession of structural engineers with diverse backgrounds and skills who work together as a team.

As outlined in section 4.2 Future skills and knowledge for sustainability, diverse teams could exist of a number of different engineering archetypes: Project Leader – defining what needs to be done and why; Sage – consultative adviser engaging in lateral, functional and in-depth thinking; Niche experts – providing specialised expertise such as in technical areas, education, code development or research and development; Digital Simulator – providing expertise in numerical modelling; Inventor – particularly in resource-responsible construction to invent new materials, structural systems, construction methods and new processes; Societal Leader – to craft, not just implement public policy.

Some engineers will possess a blend of these archetypes, but it is exactly these diverse backgrounds, skills and roles that are essential for the future. Equally important is reform of the educational and development system to support this model which can be very inspiring and powerful in attracting the brightest of the younger generation. This suggests that civil engineers will need to have a more diverse skill set.

8.3 Education, development, credentials

Educational curricula, particularly at undergraduate level, are extremely structured, packed and technically focused, leaving little flexibility or room for the broader skills that will be needed for the future. Future engineers will shape their educational experiences much more flexibly, with more emphasis in demonstrating uptake of knowledge and competencies and less on assessing applicants based on the perceived quality of their academic credentials. Hansford and Wynne's (2019) paper Future of skills: How to address changing needs post-Crossrail and Grenfell, supports these claims and stipulates attention on professional training at undergraduate level and on the job.

De Hoog (IStructE, 2020) argues that change in education and training needs to begin now. As well as teaching the traditional strong technical and analytical subjects, undergraduate engineering courses should also include arts, humanities and creativity skills in equal measure.

The ICE Professional Skills Review 2018 states that, to bring more suitable and diverse people into engineering, curricula should be improved and made attractive early in schools and colleges, better informed careers advice should be given, particularly to encourage women, and campaign to inspire people already in work to transfer to engineering. The review found that a greater variety of learning paths than the conventional single-discipline course is required to address the mix of skills in the increasingly multidisciplinary industry.

De Hoog (IStructE, 2020) believes that the engineering profession should adopt a more human-centric approach. As the world changes with advances in technology, population growth, climate change and stresses, future engineers will need to focus on their human qualities such as empathy, creativity and connection. They will redefine their essential skill set with broader training, education and diversity.

By using new technological developments to solve complex challenges faster, time is made available for engineers to focus on and contribute to societal issues. If technology allows engineers more time and access to more powerful tools, then engineers can use creativity and empathy as the motivators to drive innovative solutions for the benefit of society and the environment.

Bell (IStuctE, 2020) believes that a two-pronged strategy of career-long learning and flexible paths to developing structural engineering archetypes is essential for the engineer of the future. He also argues that the next generation must determine what is expected from each of the phases in their engineering career from formal, university training, to apprenticeship, to ongoing professional development. He stresses that along with technical specialisation, future undergraduate curricula should include a broader body of knowledge and engineering fundamentals, such as analytical and problem-solving methods. Focus should also be given to humanities and social sciences, thereby laying foundations for soft skills such as problem solving, leadership, entrepreneurship, innovation and communication.

To create a diverse team in terms of desired roles, embracing a model of engineering archetypes offers more flexibility in tailoring different paths. Consequently, the key vehicles to bringing about change are the professional and academic institutions. Crucial to this will be embracing professionals of different backgrounds, paths and roles – a richly diverse profession of structural engineering archetypes.

An ICE membership survey for the ICE Professional Skills Review in 2018 showed clearly that skills gaps are a serious problem on many projects. More than a quarter of senior managers report critical or severe challenges, owing to a lack of skills, on a large majority of their projects. However, these gaps can be reduced by teaching a broader range of skills along with technical competencies, continual and on-the-job training, upskilling and including a range of engineering archetypes.

This is the face of the future engineer: she is diverse in her skill set and knowledge of societal challenges; he is emotionally intelligent and engaged in having a positive impact on his community – they are people focused, socially driven and technologically loaded (de Hoog, 2020, p. 19).

Future engineers will be as diverse as the challenges they face.

9 ENGINEERS EMBRACING UPSKILLINGS

There are two types of evidence that can be used to demonstrate that engineers are embracing upskilling: reports of this already happening; reports of the urgent need for this to happen. These will be discussed in turn below.

9.1 Evidence upskilling is already happening

Several reports show how engineers, and sometimes those outside the sector, are upskilling for current and future engineering challenges. The Energy Institute's Future Skills report (Energy Institute, 2014) includes two case studies that show how upskilling is being embraced. The first relates to a three-year energy apprentice at Siemens and shows the speed of upskilling that is being achieved, and how apprentices' learning has a ripple effects on others.

Phil Howe's three-year NVQ Level 3 in renewables started with nine months of theoretical learning at college, then a period at the wind power training school in Newcastle, followed by working with experienced colleagues. In his final year, he was given responsibility for upskilling all Siemens' wind service technicians on to tablet use. This he achieved within the required six months. Thus, for Siemens, investment in a single apprentice produced significant upskilling of other, more experienced, employees. For an example of how this could work for civil engineers see the last two sections of the ICE blog 'How to bridge the digital generation gap', and the whole of the ICE Event video 'Good FEA needs a suspicious mind'.

The second case study shows how new training courses at NVQ Levels 1-3 suitable for those without engineering backgrounds are proving popular, and increasing technical knowledge and capacity in those currently in other (but related) sectors. The case study is of the whole energy management team at the Co-operative Group taking the NVQ Level 3 in Advanced Energy Management. Although the team had a managerial background, rather than a technical one, they all welcomed the technical training and have improved the firm's productivity by now being able to design maintenance into projects from the outset. The team has also become far more confident about asking technical questions of others in the energy industry, acquired status within the organisation and become active in a number of energy industry working groups. This shows how providing training to people with different skills backgrounds is increasing skillsets for the long term.

Another paper in Engineering a better world: Achieving the UN's Sustainable Development Goals (Kowal, RAE, 2018) shows how digital technology can provide access to virtual engineering experiments, with potentially global impact on the increase in basic engineering understanding and skills, especially for those previously unable to afford it. The Department of Engineering and Innovation at the Open University (OU) has developed a digital laboratory to provide a virtual experience of engineering experiments (RAE, 2018). Called OpenSTEM, this digital laboratory goes further than previous engineering e-learning because it delivers an interactive experience with the experiment by the student, not just a simulation of what might happen.

Furthermore, it is claimed to remove the need for physical experiments in real-world laboratories, freeing up learners to engage in experiments in times and locations that suit them, and improving the education of some engineering students who previously only studied theory. This improves diversity and inclusivity in civil engineering but may have negative consequences if those who would previously have had access to real-world practical laboratory learning cease to do so.

The first phase of the project was for students worldwide on fee-paying OU courses, but the second phase plans to make OpenSTEM available globally for free via massive online open courses (MOOCs). These will also be included in primary and secondary teacher training in India and sub-Saharan Africa with the intention of enabling increases in the numbers of engineers there.

9.2 Organisations calling for upskilling in engineering

Another way this challenge can be understood is in terms of the organisations calling for significant increases in engineering-related upskilling. This sub-section focuses on this aspect.

For instance, the RAE report Engineering priorities for our economy and society (RAE, 2019) urges the Government to fund 40 hours of ring-fenced continuing professional development (CPD) for STEM and design teachers, and properly-costed funding for FE engineering programmes, both to attract more pupils and people into these courses, and to provide a higher-quality learning experience on those courses. In its report, Engineering a better world: Achieving the UN's SDGs, the RAE calls for engineering courses to have a stronger focus on solving social and environmental courses (as well as for engineering courses to be added to social science and humanities courses).

Similarly, in its report on Automation and the Future of Work, the RAE emphasises the critical need for improvements to education and training, in particular for high levels of investment in training for in-demand skills, especially since the education system adapts more slowly to technological change than business and for the development of apprenticeships, lifelong learning and career support, and MOOCs, so that people are adaptable at work in the automation context. In addition, the professional engineering institutions are to be flexible in their response to the new jobs and careers developing as a result of automation. This suggests that ICE should at least consider changing its membership requirements or provide flexibility in interpreting and applying criteria.

Mace's (2017) report Moving to Industry 4.0 shows how a leading construction firm is embracing the transformation of the industry it expects from Industry 4.0. It argues that there are a number of key ways in which construction will have to change as a result. Moving to Industry 4.0 will be a challenge for every part of the asset lifecycle. For instance, boundaries between job roles will become blurred, and there will be increased demand for generalists who can combine multiple functions.

This raises the question of whether there will even be a defined civil engineer role. However, there were three key areas where Mace found that skills were lacking: augmented reality; advanced data analytics; advanced energy creation and storage. The majority of respondents (70% plus) felt that each of these technologies would become widespread by the mid-2020s. Considering all 12 technologies in the research, employers felt that skills shortages were at least moderate, if not severe.

Chapter 4 of this report is by a former Bank of England economist, and makes predictions about the type and extent of likely job losses in construction under scenarios of slow, moderate, and fast-paced change. For instance, the number of plant operatives are predicted to fall from 42,040 to 2,490 as a result of automation. It also recommends retraining opportunities for those construction workers in the category where demand currently outstrips supply: "non-construction professional, technical, IT and other office-based staff" (p. 7). The response to this needs to be an acceleration in the use of new technology in training, inform lifelong learning decisions, and revolutionise traditional education programmes.

Lastly, it is important to recognise that these calls for rapid upskilling will best be met if the education and training on offer is exciting. For instance, Goldby (Energy Institute, 2014) explains how "inspiration, inspiration, inspiration" at key moments in his career was pivotal to his distinguished success. Consequently, the engineering sector needs to focus on providing that inspirational education and training. Paul Jackson, CEO of Engineering UK (Energy Institute, 2014), echoes this: for him, engineering education should be "information with inspiration".

Thankfully, it is an extremely exciting time to be an engineer. How do we inspire people – existing civil engineers and those yet to join the profession – to be a future civil engineer?

Civil Engineer of the Future Reading list - by identified themes

Please note: some items appear in multiple categories.

1. New business models

Hedley Smyth (2018) - Castles in the Air? The Evolution of British Main Contractors (UCL Bartlett School of Construction and Project Management)

ACE - Future of Consultancy – Overview

ACE - Future of Consultancy – Value based business models

ACE - Future of Consultancy – Global export strategy

RAE (2016) - Engineering a Better World: Achieving the United Nations Sustainable Development Goals

RAEng (2018) - Automation and the Future of Work

Browne, D (2018) - 13th time lucky: a new blueprint for the future of high performing infrastructure has been unveiled by the Project 13 initiative (Institution of Civil Engineers)

de Hoog, T (2020) - The future is human (Special issue: 2040 vision - the future of the profession Struct Engr, v98 n1 Jan)

Foxell, Mark (2018) - Professionalism for the Built Environment

PCubed (2019) - Service Innovation – Accelerating Growth in Tomorrow's Workplace (video)

McGilveray, H and Pierce, S (2020) - The Specialist generalist engineer (Special issue: 2040 vision - the future of the profession) [Role of the engineer]. (Struct Engr, v98 n1 Jan)

Raconteur (2018) - The Future of Construction

Susskind & Susskind (2015) - The Future of the Professions: How Technology will Transform the Work of Human Experts

Fischer, B (2015) - The End of Expertise (Harvard Business Review)

Clark, E & Ibell, T - An unprecedented era of opportunity (IStructE)

Bell, G - An expansive vision for structural engineers (IStructE)

McGilveray, H & Pierce, S - The specialist-generalist engineer (IStructE)

Burrows, S - Return of the master architect (IStructE)

Sinek, S - The infinite game

Project 13 framework

Project 13 Commercial Handbook

2. Profile of Construction Sector Workers

ACE - Future of Consultancy Overview

Construction Leadership Council (2019) - Future Skills Report

RAEng (2019) - Engineering priorities for our future economy and society

RAEng (2018) - Automation and the future of work

Karakhan, Ali A; Gambatese, J; and Simmons, D R - Development of Assessment Tool for Workforce Sustainability (Journal of Construction Engineering and Management, April 2020)

Naoum, S; Harris, J; Rizzuto, J; and Egbu C (2019) - Gender in the Construction Industry: Literature Review and Comparative Survey of Men's and Women's Perceptions in UK Construction Consultancies (Journal of Management in Engineering, 36:2, Online publication date: 1-Mar-2020)

Raconteur (2018) - Future of Engineering (Raconteur Media, in association with the IET (overview report))

Raconteur (2018) - Future of Construction

The National Centre for Universities and Business (2019) Talent 2050: Skills and Education for the Future of Engineering

Isaac, P & Bergsagel - Staying relevant – new ways to assess engineering aptitude (IStructE)

3. Digital

Balfour Beatty - Innovation 2050 – A Digital Future for the Infrastructure Industry (see also Soundcloud and youtube animations)

Bew, Mark - PhD Thesis in BIM Level 4

Burke, M S (2018) - The future of infrastructure. Expert opinions from around the world on the challenges and opportunities ahead. AECOM (10,000 responses from several global cities, individual summaries for each city)

Clipsom D - Digital skills for future engineers (IStructE)

De Hoog T - The future is human (IStructE)

Debney P - The engineer of the future is a centaur (IStructE)

Deloitte - Industry 4.0: At the intersection of readiness and responsibility

Ericsson - Industry 4.0

GE - Case study of petrochemical processing using digital

Gigabit magazine (2018) – McKinsey: Demand for technological skills set to rise by 55%

ICE - Professional Skills Review (2018)

IPA (2016) - National Infrastructure Delivery Plan 2016-2021

IMechE - Industry 4.0 report

KPMG - Beyond the hype of i4.0

KPMG - InfraTech is here

Mace - Insights 2017 – Moving to Industry 4.0

The Manufacturer and Oracle - Industry 4.0 UK Readiness Report

McKinsey Global Institute (2019) - Future Skills: Six approaches to close the skills gap

McKinsey Global Institute (2018) - Skill shift: Automation and the future of workforce

McKinsey & Company (2017) - The digital future of work: what skills will be needed?

NIC - Connected Future

NIC - Smart Power

PTC.com - Automation Alley Technology in Industry report

PwC - Global Digital Operations Study 2018 – Digital Champions

PwC - Industry 4.0: Building the digital enterprise

RAE (2019) - Engineering priorities for our future economy and society

RAE (2016) - Engineering a Better World: Achieving the United Nations Sustainable Development Goals

Sheffield P (2019) - The future is already here - Civil Engineering at the cutting edge. ICE President Paul Sheffield's presidential address.

Department for Transport (2017) - Transport Infrastructure Efficiency Strategy

Department for Transport, Highways England, HS2, Network Rail, Transport for London (2019) - The Transport Infrastructure Efficiency Strategy: One Year On

RAEng (2018) - Automation and the Future of Work

4. Sustainability and Net Zero

ACE - Future of Consultancy Overview

ASCE (2007) - The Vision for Civil Engineering in 2025

ASCE - Future world vision: infrastructure reimagined

Burke, M S (2018) - The future of infrastructure. Expert opinions from around the world on the challenges and opportunities ahead. AECOM (10,000 responses from several global cities, individual summaries for each city)

Energy Institute (2014) - Future Skills

IPA (2016) - National Infrastructure Delivery Plan 2016-2021

Krumdieck S (2020) - Transition Engineering: Building a Sustainable Future

NIC - National Infrastructure Assessment

NIC - Anticipate, React, Recover – resilient infrastructure systems

RAE (2016) - Engineering a Better World: Achieving the United Nations Sustainable Development Goals

Bell, G R (2020) - An expansive vision for structural engineers (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

Civil Engineering Body of Knowledge (2019) - Preparing the Future Civil Engineer

De Hoog, T (2020) - The future is human (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

IStructE (2020) - 2040 Vision. Will changing attitudes and technological advances usher in a sustainable and human centric future for structural engineering? (Special issue, The Structural Engineer, Vol. 98, Issue 1. Jan 2020)

Cook M - Turning climate commitment into action (IStructE)

Clark E; Ibell T - An unprecedented era of opportunity (IStructE)

Fivet C; Brutting J - Nothing is lost, nothing is created, everything is re-used: structural design for a circular economy (IStructE)

Moynihan M - Held to carbon account: the end of 'bog standard' new build? (IStructE)

Campbell A; Cooper M; Waugh A - Manufacturing buildings for people and planet (IStructE)

Lathem S; Neumann M; Hayden N (2013) - The Socially Responsible Engineer: Assessing Student Attitudes of Roles and Responsibilities (Journal of Engineering Education 10.1002)

McGilveray, H; Pierce, S. (2020) - The Specialist generalist engineer (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

Oswald Beiler; Michelle R (2015) - Teaching sustainability topics to attract and inspire the next generation of civil engineers. (Journal of Professional Issues in Engineering Education and Practice, v 141, n 2, April 1, 2015)

Raconteur (2018) - Future of Engineering (Raconteur Media, in association with the IET (overview report))

Reid, Robert L (2015) - Focused on the Future (Civil Engineering Magazine Archive Vol. 85, Issue 7 July 2015)

Rogers, C - Engineering future liveable, resilient, sustainable cities using foresight. (Proceedings of the Institution of Civil Engineers - Civil Engineering Vol. 171 Issue 6, November 2018, pp. 3-9)

Ronalds T - Diversity of materials (IStructE)

Sheffield P (2019) - The future is already here - Civil Engineering at the cutting edge. ICE President Paul Sheffield's presidential address.

Shuster, L A (2019) - What lies ahead? (Civil Engineering (ASCE), Volume 89, Issue No 6, June 2019, pp 56-63)

Wise C (2012) - No Hiding Place… measure design by performance

5 Productivity

ACE - Future of Consultancy – Overview

ACE Future of Consultancy – Value-based business models

ACE Future of Consultancy – Global export strategy

Hedley Smyth (2018) - Castles in the Air? The Evolution of British Main Contractors (UCL Bartlett School of Construction and Project Management)

Burke, M S (2018) - The future of infrastructure. Expert opinions from around the world on the challenges and opportunities ahead. AECOM (10,000 responses from several global cities, individual summaries for each city)

Deloitte - Industry 4.0: At the intersection of readiness and responsibility

ICE - Professional Skills Review (2018)

IMechE - Industry 4.0 report

IPA (2016) - National Infrastructure Delivery Plan 2016-2021

KPMG - Beyond the hype of i4.0

KPMG - #InfraTech is here

Mace - Insights 2017 – Moving to Industry 4.0

NIC - National Infrastructure Assessment

RAEng (2019) - Engineering priorities for our future economy and society

RAE (2016) - Engineering a Better World: Achieving the United Nations Sustainable Development Goals

Department for Transport (2017) - Transport Infrastructure Efficiency Strategy

Department for Transport, Highways England, HS2, Network Rail, Transport for London (2019) - The Transport Infrastructure Efficiency Strategy: One Year On

Browne, D (2018) - 13th time lucky: a new blueprint for the future of high performing infrastructure has been unveiled by the Project 13 initiative (Institution of Civil Engineers)

de Hoog, T (2020) - The future is human (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

McGilveray, H; Pierce, S. (2020) - The Specialist generalist engineer (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

Raconteur (2018) - Future of Engineering (Raconteur Media, in association with the IET (overview report))

Reid, Robert L (2015) - Focused on the Future (Civil Engineering Magazine Archive Vol. 85, Issue 7 July 2015)

Shuster, L A (2019) - What lies ahead? (Civil Engineering (ASCE), Volume 89, Issue No 6, June 2019, pp 56-63)

Fischer, B (2015) - The End of Expertise (Harvard Business Review)

Wise C (2012) - No Hiding Place… measure design by performance

National Centre for Universities and Business (2019) - Talent 2050: Skills and Education for the Future of Engineering.

Fivet C; Brutting J - Nothing is lost, nothing is created, everything is re-used: structural design for a circular economy (IStructE)

Bowkett N; Goring P; Mairs D - The Jump Factory – reaching new heights in construction productivity (IStructE)

6. Foresighting Methods

Reid, Robert L (2015) - Focused on the Future (Civil Engineering Magazine Archive Vol. 85, Issue 7 July 2015)

Rogers, C - Engineering future liveable, resilient, sustainable cities using foresight. (Proceedings of the Institution of Civil Engineers - Civil Engineering Vol. 171 Issue 6, November 2018, pp. 3-9)

Shuster, L A (2019) - What lies ahead? (Civil Engineering (ASCE), Volume 89, Issue No 6, June 2019, pp 56-63)

7. System level thinking

ACE - Future of Consultancy – Overview

Hedley Smyth (2018) - Castles in the Air? The Evolution of British Main Contractors (UCL Bartlett School of Construction and Project Management)

ASCE (2007) - The Vision for Civil Engineering in 2025

Burke, M S (2018) - The future of infrastructure. Expert opinions from around the world on the challenges and opportunities ahead. AECOM (10,000 responses from several global cities, individual summaries for each city)

ICE - Professional Skills Review (2018)

IPA - National Infrastructure Delivery Plan

NIC - National Infrastructure Assessment

NIC - Anticipate, React, Recover – resilient infrastructure systems

NIC - Regulation (Strategic investment and public confidence)

NIC - Connected Future

NIC - Smart Power

RAEng (2019) - Engineering priorities for our future economy and society

RAE (2016) - Engineering a Better World: Achieving the United Nations Sustainable Development Goals

UFF, J (2016) - UK Engineering 2016: an independent review

RAEng (2018) - Automation and the Future of Work

Bell, G R (2020) - An expansive vision for structural engineers (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

Civil Engineering Body of Knowledge (2019) - Preparing the Future Civil Engineer

Browne, D (2018) - 13th time lucky: a new blueprint for the future of high performing infrastructure has been unveiled by the Project 13 initiative (Institution of Civil Engineers)

De Hoog, T (2020) - The future is human (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

McGilveray, H; Pierce, S (2020) - The Specialist generalist engineer (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

Reid, Robert L (2015) - Focused on the Future (Civil Engineering Magazine Archive Vol. 85, Issue 7 July 2015)

Rogers, C - Engineering future liveable, resilient, sustainable cities using foresight. (Proceedings of the Institution of Civil Engineers - Civil Engineering Vol. 171 Issue 6, November 2018, pp. 3-9)

Sheffield P (2019) - The future is already here - Civil Engineering at the cutting edge. ICE President Paul Sheffield's presidential address.

Shuster, L A (2019) - What lies ahead? (Civil Engineering (ASCE), Volume 89, Issue No 6, June 2019, pp 56-63)

Clark E; Ibell T - An unprecedented era of opportunity (IStructE)

Fivet C; Brutting J - Nothing is lost, nothing is created, everything is re-used: structural design for a circular economy (IStructE)

Burrows, S - Back to the Future: The Return of the Master Architect

Sinek, S - The infinite game

8 Diversity in construction

ASCE (2007) - The Vision for Civil Engineering in 2025

Construction Leadership Council (2019) - Future Skills Report

ICE - Professional Skills Review (2018)

Mace - Insights 2017 – Moving to Industry 4.0

McCall, R (2018) - Year of engineering 2018

PwC - Global Digital Operations Study 2018 – Digital Champions

Reeves, D (2017) - Find Your Future in Engineering

RAEng (2019) - Engineering priorities for our future economy and society

RAE (2016) - Engineering a Better World: Achieving the United Nations Sustainable Development Goals

UFF, J (2016) - UK Engineering 2016: an independent review

Bell, G R (2020) - An expansive vision for structural engineers (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

Civil Engineering Body of Knowledge (2019) - Preparing the Future Civil Engineer

De Hoog, T (2020) - The future is human (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

Hansford, M and Wynne, A (2019) - Future of skills (New Civil Engineer, June 2019, pp 29-40)

Karakhan, Ali A; Gambatese, J; Simmons, D R - Development of Assessment Tool for Workforce Sustainability (Journal of Construction Engineering and Management, April 2020)

Lathem S; Neumann M; Hayden N (2013) - The Socially Responsible Engineer: Assessing Student Attitudes of Roles and Responsibilities (Journal of Engineering Education 10.1002)

McGilveray, H; Pierce, S (2020) - The Specialist generalist engineer (Struct Engr, v98 n1 Jan Special issue: 2040 vision - the future of the profession)

Naoum S; Harris J; Rizzuto J; Egbu C (2019) - Gender in the Construction Industry: Literature Review and Comparative Survey of Men's and Women's Perceptions in UK Construction Consultancies (Journal of Management in Engineering, 36:2, Online publication date: 1-Mar-2020)

Raconteur (2018) - Future of Engineering (Raconteur Media, in association with the IET (overview report))

Raconteur (2018) - Future of construction

Reid, Robert L (2015) - Focused on the Future (Civil Engineering Magazine Archive Vol. 85, Issue 7 July 2015)

Sheffield P (2019) - The future is already here - Civil Engineering at the cutting edge. ICE President Paul Sheffield's presidential address.

Jackson, P (2019) - Talent 2050: Skills and Education for the Future of Engineering

Isaac P; Bergsagel D - Staying relevant – new ways to assess engineering aptitude (IStructE)