Transitioning to engineering practice

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ABSTRACT

Transition from education to practice can be troublesome for many early-career engineers because expectations, habitual work practices and values tend to conflict with realities of engineering workplaces. Emerging technologies referred to as 'Industry 4.0' or the 'fourth industrial revolution' have prompted many to argue for students to develop improved socio-technical skills. Understandings of practice emerging from contemporary research could help educators shape a new generation of engineers with more appropriate abilities to restore global productivity growth and transform economies to eliminate greenhouse emissions in a short enough time to limit human-induced global warming. However, so far, explicit curriculum reforms addressing graduate attributes and workplace skills have not resulted in significant employability improvements. This paper argues that assessment practices and curriculum gaps may be acting as an implied or hidden curriculum shaping student expectations and values. This paper proposes ways to overcome these curriculum deficits in higher education institutions and also workplace education interventions. These changes could help educate engineers about productivity improvement, commercial and social value generation, business requirements and entrepreneurship. Changes like these will be needed to achieve sustainable development goals, especially in developing countries.

Introduction

In 1975 I started teaching in an engineering school after four years work in commercial defence and aerospace engineering. I knew that what I was teaching bore little resemblance to practice. Along with many others around the world I tried to bridge that gap many times in my classes, with some modest success now and then, mainly with open-ended design projects. However, the disjuncture between engineering practice and education has remained essentially unchanged despite efforts by a host of education reformers.

I write with multiple viewpoints: I have decades of experience as an engineering educator, a researcher, an engineering employer and a supervisor of early-career engineers. These experiences were linked: several of the young engineers I supervised had studied in my courses. I researched engineering practice and education to understand apparent contradictions stemming from my personal experiences employing engineers in South Asia (Trevelyan Citation2010b, Citation2014a, Citation2014b, Citation2016; Trevelyan and Williams Citation2018b).

Misalignments between engineering education and practice have been debated for many decades and many engineering graduates still endure troublesome early-career transitions. For most of them engineering, in practice, is quite different to what they expected: only a comparatively small part seems to align with their technical identities (Anderson et al. Citation2010; Trevelyan Citation2010b, 17). In addition, graduates emerge with many misunderstandings about engineering practice and the nature of the work they will be expected to perform (Korte, Brunhaver, and Sheppard Citation2015; Trevelyan Citation2014a). Some of these misunderstandings may persist through their careers (Robinson Citation2013). In one of the author's studies, a novice engineer exclaimed in an interview ‘I have been here six months and I still have absolutely no idea about what I am expected to do here: I feel totally incompetent’. Far too many graduates never even work as an engineer (Trevelyan and Tilli Citation2010) in part due to similar misunderstandings.

Students also develop inappropriate practices in the course of project work intended to provide authentic learning experiences, partly as a result of socialisation through their years at university (Leonardi, Jackson, and Diwan Citation2009). They take these inappropriate practices with them into their workplaces. As a result, employers have long complained about graduate shortcomings, particularly team work and communication skills (e.g. Grinter Citation1955; Leonardi, Jackson, and Diwan Citation2009, 401).

University engineering education today (Sheppard et al. Citation2009) combines elements of nineteenth century schools created to train an industrial workforce and consumer society along with traditions inherited from universities and madrassasFootnote1 that evolved over many centuries (Petersen Citation2015, 14–19). As the final phase in a 18–20 year long journey through formal education, engineering education cannot easily be separated from its context. One aspect that stands out in a comparison with medical education, another profession relying on specialised technical knowledge, is the level of practice knowledge among teaching staff. Almost all of the teaching past the half way point in a typical medical school is performed by people practicing their profession daily in clinics and hospitals. Engineering schools, on the other hand, have few if any people with experience of engineering outside brief stays in research laboratories (e.g. Cameron, Reidsema, and Hadgraft Citation2011). Faculty tend to value analysis over design and narrowly conceive of practice in terms of solving technical problems (Pawley Citation2009; Quinlan Citation2002). While many engineering schools also seek opinions from engineers on industry advisory boards, faculty knowledge of current industry practice is tenuous at best. The main guidance on professional needs for the last two decades has been a concise list of engineering competencies and generic graduate attributes (Male, Bush, and Chapman Citation2009; Passow and Passow Citation2017). They serve as a proxy for knowledge of engineering practice and come with an implied assumption that graduates who develop these competencies and attributes will somehow meet the needs of their employers. However, Shippmann et al. (Citation2000) has pointed out the weakness of this approach, that understandings about competencies depend on contextual knowledge which is often scarce in the academy.

Over the last three decades, we have built more detailed research-based understandings of engineers at work, and this editorial will suggest ways to build on this knowledge in order to provide graduates with a more appropriate transition to practice. Caution is needed however. Designing university curricula around workplace skills is a widely contested idea and recent research casts doubt on the benefits of doing so. In addition, implied, hidden and null curricula could be promoting values that conflict with effective workplace practices. This editorial will suggest that addressing engineering practice in a framework of social science theory may be a productive approach for future research aimed at improving engineering education, a project that could require many decades. In the meantime, workplace interventions might provide a more effective interim solution.

Knowledge of practice

Research studies tell us that engineering is a collaborative enterprise based on specialised technical expertise distributed among the participants, accessed through a network of trusting relationships shaped by workplace social norms. This understanding has emerged from recent research reports (among others Anderson et al. Citation2010; Bailey and Barley Citation2010; Barley and Bechky Citation1994; Barley and Orr Citation1997; Bechky Citation2003; Bornasal et al. Citation2018; Bucciarelli Citation1994; Buch Citation2015, Citation2016; Buch and Andersen Citation2015; Chilvers and Bell Citation2013; Coelho Citation2004; Darr Citation2000, Citation2002; Davis, Vinson, and Stevens Citation2017; Faulkner Citation2007; Gainsburg Citation2006; Gainsburg, Rodriguez-Lluesma, and Bailey Citation2010; Goold and Devitt Citation2013; Horning Citation2004; Hubert and Vinck Citation2013; Itabashi-Campbell and Gluesing Citation2013; Jacobs Citation2010; Jesiek et al. Citation2019; Johri Citation2012; Jonassen, Strobel, and Lee Citation2006; Kaplan and Vinck Citation2013; Kilduff, Funk, and Mehra Citation1997; Korte Citation2018; Lagesen and Sørensen Citation2009; Lam Citation1997, Citation2000, Citation2005; Mehri Citation2005; Mukerji Citation2009; Orr Citation1996; Perlow Citation1999; Petersen Citation2015; Rooney et al. Citation2013; Sandberg Citation2000; Trevelyan Citation2010b, Citation2013a, Citation2013b, Citation2014a; Vinck Citation2003, Citation2019; Williams and Figueiredo Citation2013, Citation2015).

Engineering practice largely consists of a series of elaborate socio-technical performances that are remarkably similar across all disciplines. These performances have been described as informal teaching and learning, informal leadership, technical coordination, mobilising human resources, project management and technical problem solving framed by multi-party negotiations (Blandin Citation2012; Itabashi-Campbell and Gluesing Citation2013; Rottmann, Sacks, and Reeve Citation2015; Trevelyan Citation2014a, Ch 7–13). (The widely used terms ‘project management’ and ‘professional skills’, formerly ‘soft skills’, describe some elements of these performances but none of the socio-technical complexities.) They enable engineers to leverage shared technical insights to anticipate, plan, organise and coordinate a host of skilled contributions by many people, preserving the original technical intentions well enough so that ultimate artefacts and systems meet forecast levels of technical and commercial performance. Engineering performance limits, therefore, depend as much on human social and intellectual limitations as the laws of physics.

Trevelyan (Citation2014a, Ch 4) also identified a small number of self-taught 'expert' engineers earning considerably more than their peers. They were able to reflect on their performances, at least in part, in terms of commercial value creation (Trevelyan and Williams Citation2018a, Citation2018b). These engineers were creating sufficient value for their employers to justify high rewards, particularly in emerging economies.

Some immediate engineering challenges

The recent research on engineering practice may have come just in time. Today we face the need for rapid technological change to eliminate greenhouse emissions in the next 25–35 years, the deadline set recently by the Intergovernmental Panel on Climate Change (Allen et al. Citation2018). This will be one of the greatest social and technological challenges for humanity and simultaneously one of the greatest opportunities for engineers with strong social, professional and technical skillsets.

In the next few years we will also need large productivity gains to at least maintain living standards as we transform our technologies to reduce resource consumption while populations age and the climate warms. While engineers are not the only people who can improve productivity, they are important contributors. Current signs of weakness in productivity growth include:

Large reductions in global productivity growth since the mid-2000s (Manyika et al. Citation2015);

Persistent productivity gaps between advanced and emerging economies that have not shifted in several decades (Manyika et al. Citation2015, 48); and

Appalling completion rates for engineering projects, especially large ones (Merrow Citation2011; Trevelyan and Williams Citation2018a; Young Citation2012).

There are two directly related aspects of engineering education that, once identified, seem obvious on reflection:

Engineering students do not learn that productivity improvement is the engineering raison d'être, its ultimate purpose. If asked about the purpose of engineering most students mention technical problem solving and a vague notion that engineering improves the world, without explaining how: productivity is rarely if ever mentioned.

Engineering students do not learn engineering practice: how to deliver practical results in line with expectations. Therefore it is not so surprising to find low completion success rates for engineering projects, largely due to collaboration weaknesses (Trevelyan Citation2014a; Trevelyan and Williams Citation2018a). While students are often required to work in groups, they are seldom if ever taught how to collaborate effectively, let alone with the diverse cast of stakeholders that engineers confront in the workplace (Sheppard et al. Citation2009, 67).

If most engineers, especially in emerging economies, were to understand that their task is to improve productivity, and to acquire the socio-technical capabilities that today have been mastered by a mere handful of expert engineers, we might see renewed global productivity growth. Then we would have a much better chance of transforming our technologies and societies to eliminate much of the poverty we see today and achieve the new set of UN Sustainable Development Goals (United Nations Development Programme (UNDP) Citation2017; World Federation of Engineering Organizations (WFEO) Citation2018). We would also have a much better chance of eliminating greenhouse emissions in time for the IPCC deadline.

That the ultimate purpose of engineering is productivity improvement could readily be learned by undergraduate engineers with minimal curriculum changes. However, in this short editorial, I also suggest that universities may not yet be the best place for students to learn about engineering practice, how to deliver practical results in line with expectations, no matter how well the curriculum might be designed with that objective in mind. Instead, I will suggest that higher education institutions and firms collaborate with governments to ensure that engineers learn engineering practice in the workplace for the benefit of enterprises, societies and humankind.

Employability debates

Most research on the transition from education to the workplace has focused on employability: the likelihood of productive employment soon after graduation. However, in the case of engineering, recent research points to more damaging economic consequences from education-practice misalignments such as weakening global productivity improvement (Trevelyan and Williams Citation2018a).

Concerns about the transition to the workplace are neither new nor restricted to engineering. Many studies have shown only slight if any relationship between academic performance and success at work (Gibbs and Simpson Citation2004).

Employability concerns have sparked vigorous debates in higher education. On one side we typically find governments and employers (or their representative associations) arguing that universities should 'produce' or 'train' 'job-ready' graduates, young people who can 'hit the ground running'. Many of these people advocate strongly for specific workplace skills (or competencies) to be explicitly taught to students so that they can quickly become productive employees with the least possible investment in training by the employers. Most often, universities are urged to teach communication, numeracy, IT and learning how to learn at a higher level (Mason, Williams, and Cranmer Citation2009, 3).

Employability debates in engineering education have a long history. For example, the electrical engineering programme at MIT emerged in the early twentieth century from the tension between large corporate sponsors seeking qualified manpower to address quality control issues in factories and senior faculty who asserted that a broad foundation in mathematics and science was essential for graduates who would become future industry leaders (Carlson Citation1988). Proposals debated by the American Society for Engineering Education (ASEE) to strengthen scientific and mathematical foundations of engineering curricula prompted calls by employers for greater 'emphasis upon the inability of engineers to express themselves in clear, concise, effective, and interesting language and … an acquaintance with the humanities and social sciences' (Grinter Citation1955). Similar pressure led to the EC2000 reform and standardisation effort by the US Accreditation Board for Engineering and Technology (ABET). The aim was to define education outcomes, a concise set of competencies required for engineering careers, and also to encourage students to learn the context of engineering in addition to engineering science (Besterfield-Sacre et al. Citation2000).

Many later reformers have urged the adoption of new curricula such as CDIO (Crawley et al. Citation2007) or new teaching methods such as problem-based learning (PBL) (Edström and Kolmos Citation2014; Kolmos and De Graaff Citation2007). These paralleled many similar curriculum innovations and reform efforts (e.g. Brunhaver et al. Citation2017; Duderstadt Citation2008; Froyd and Ohland Citation2005; Galloway Citation2008; Kolmos and Holgaard Citation2018; Sheppard, Pellegrino, and Olds Citation2008).

Most recently, many have cited emerging technologies as a further reason for developing new and improved socio-technical skills and leadership abilities. Widely referred to as 'Industry 4.0' or a 'fourth industrial revolution', these technologies are said to include ubiquitous artificial intelligence in devices such as mobile phones, high speed data networks, the internet of things, additive manufacturing, 'big data' and robotics (Maynard Citation2015; Schwab Citation2015; VDI Nachricht Citation2011). Caution is needed with technology forecasts, however. Expected productivity improvements resulting from the adoption of digital technologies have not, so far, eventuated (Bughin et al. Citation2018), just as 1970s forecasts about the displacement of factory workers by industrial robots turned out to be almost completely mistaken. Perhaps, as engineers, we should refocus our attention on the production of goods and services rather than information.

On the other side of the employability debate academics argue that universities educate students for life and provide an essential space to explore intellectual ideas and debates. They argue, for example, that the skills required to be a historian or an engineer are skills needed to be successful in life (Cranmer Citation2006, 182). They also argue that these attributes, much more than specific job skills, help people develop as leaders in their organisations and their professional fields and therefore there is no need to divert valuable curriculum space to specific occupational skills. Workplace competencies, they argue, are better learned in workplaces.

Large government investments in higher education to increase participation, particularly in tertiary education, have raised the importance of employability (Mason, Williams, and Cranmer Citation2009; Star and Hammer Citation2008). Economic considerations require that a minimal proportion of graduates remain under-employed, or in jobs in fields unrelated to their education.

Guilbert et al. (Citation2016) describe several other dimensions of employability. Employers want to be able to recruit appropriately skilled workers when needed who will work productively with minimal additional training. Graduates, the other main partners, are more interested in optimising their career prospects. Employability, they argue, is also shaped by social constructs. People with different appearance, foreign accents, or names associated with certain countries can find it much harder to gain employment even with the same capabilities as local graduates. These social constructs are only indirectly influenced by education (Guilbert et al. Citation2016).

There are weaknesses on both sides of the employability debate. There is little evidence that skills instruction makes much difference to graduate outcomes (Cranmer Citation2006, 182; Mason, Williams, and Cranmer Citation2009, 17). The only factor that makes a significant difference is structured work experience (such as co-ops and internships) (Edwards et al. Citation2015; Mason, Williams, and Cranmer Citation2009, 24). In the engineering education context, evaluations of the ABET EC2000 and other curriculum reforms have shown only small shifts in student and employer perceptions (Lattuca, Terenzini, and Volkwein Citation2006). A persistently high proportion of graduates in many countries remain underemployed or in unrelated occupations, a significant economic penalty considering the high cost of engineering courses (e.g. Trevelyan and Tilli Citation2010). Research has shown that a deep understanding of the contemporary workplace by teaching faculty is needed for skills instruction to have an impact (Bennett Citation2016) and, as we have seen, this is currently not available in engineering schools.

Research on engineering workplace transitions

Transition from engineering education to the workplace is, along with engineering practice itself, a relatively under-studied aspect of engineering education.

Aspects of the engineering education-practice gap have been identified in several studies focusing on early career engineers in their first jobs. A troubling finding identified in several studies is that academic performance has little correlation with job performance (Lee Citation1986; Newport and Elms Citation1997). A persistent theme is socialisation: building relationships. Findings have pointed to the critical importance of helpful mentoring relationships with experienced engineers (Davis, Vinson, and Stevens Citation2017; Korte Citation2009; Lee Citation1986, Citation1994). A study comparing psychology and engineering students showed how the former were better prepared for socialisation (Dahlgren et al. Citation2006). Studies of workplace learning have highlighted the importance of tacit and implicit knowledge (Eraut Citation2000, Citation2004, Citation2007; Eraut et al. Citation2000), types of knowledge that are hardly mentioned in formal tertiary studies. Later studies have emphasised the importance of socialisation in identity formation (Huff Citation2014; Johri Citation2012; Korte Citation2017; Korte, Brunhaver, and Sheppard Citation2015; Korte, Sheppard, and Jordan Citation2008). A series of emerging studies have revealed similar findings (e.g. Bakht Citation2018; Kovalchuk et al. Citation2017; Lutz Citation2017; Paretti et al. Citation2017; Villanueva et al. Citation2018).

Authentic practice experiences such as industry design projects have been a significant part of engineering curricula for two decades, longer in some institutions. However, Leonardi, Jackson, and Diwan (Citation2009) has shown how students enact popular engineering stereotypes to fit in with their peers and adopt counterproductive work practices in project teams that they later carry into their workplaces, despite the best efforts of their teachers to encourage effective planning and collaboration. No matter how authentic, students carry no ongoing responsibilities for their project work after the submission date. This contrasts with workplaces where engineers often assume ongoing responsibilities that endure for years, even decades after their designs or analyses have been completed.

Beyond explicit curriculum

Given what we now know about engineering practice, these results might have been predicted. In this section, I introduce some curriculum gaps that might help to explain why it has been so difficult to achieve meaningful change through changes to the explicit curriculum or pedagogy alone (Sinclair and Ghory Citation1979; Wilson Citation2006). Consideration of some further curriculum dimensions might also help to explain this. Further research studies are needed to explore the influence of these dimensions in more detail.

Finance

Finance shapes all aspects of engineering practice. In an engineering school, however, money is usually seen as a topic of marginal importance to be dealt with by a business school, requiring relatively trivial mathematical skills compared to engineering. While many engineers study business in MBA and commerce courses, it was surprising to find in our studies that these engineers found it just as hard to describe the commercial value arising from their work as others without any business studies qualifications (Crossley Citation2011; Singh Citation2015). This might be explained by weak theoretical links between engineering and business. Without theory, it is hard for students to learn how business and engineering are related (Trevelyan and Williams Citation2018a, Citation2018b). Whether new insights from research will help bridge this conceptual gap remains to be seen. It also remains to be seen whether the extensive adoption of entrepreneurship programmes in universities can help to address this weakness.

Communication

There is a common misconception in engineering schools that communication is defined in terms of transferring information (usually one-way, eg a written solution in a technical report from an engineer to a client, often referred to as the final part of problem solving). Communication is much more than merely transferring information. In practice, oral communication and physical presence are the foundations on which trusting relationships depend. These relationships are important for the elaborate technical collaboration performances that form the greater part of an engineers' work (Trevelyan Citation2014a). For example, many young engineers encounter frustration on finding that no one has the interest or time to read a carefully crafted, detailed technical report, even the covering email.Footnote2 They soon learn that a technical presentations are ineffective for coordinating work on a construction site where learning from others is critical. Trevelyan (Citation2014a) identified over 100 similar misconceptions among students.

Infrastructures and values shaped by absences

Curriculum reformers often encounter stiff opposition from colleagues when they advocate restructuring to enable students to learn even the most basic elements of practice (e.g. Juhl and Buch Citation2018). Paradoxically, this opposition could have been justified in the past. Rather than the common argument in faculty discussions, that introducing elements of practice might displace technical content, stronger evidence comes from systematic statistical evidence from employability studies described above.

Petersen and Buch (Citation2016) built on the notion of 'infrastructure' to describe practices that reinforce organisations and inhibit change, even when change is needed. For example, awarding grades for individual performance from the earliest classes in primary school may be steadily reinforcing a valuing of individual effort and self-control in response to a challenge. In engineering practice, individual efforts, often made visible by working long hours, can undermine relationships and the essential collaboration on which, ultimately, engineering performances depend. Engineers mostly achieve results by collaboration, influencing the actions of all the other people who deliver the ultimate product or service. Influence depends on trusting social relationships. Yet time spent on socialising, influencing, and building relationships, often regarded as 'politicking' in an engineering workplace, even wasted time, is not seen as 'hard core engineering' (Bailyn and Lynch Citation1983, 280). In my teaching, I encountered strong emotional resistance from some students in team projects when their individual assessments depended on influencing peers to collaborate effectively. Later, reflection helped identify an association between the strength of student resistance and the persistent reinforcement through individual grading that builds the notion that education prioritises 'my individual effort' over collaboration with other people.

Another aspect of assessment practices in education is the almost complete reliance on written assessments (or marking items in a multiple choice questionnaire). This could be reinforcing an implied association between grades (the primary reward in education) and written communication. This, in turn, could explain the tendency for graduates to prioritise written communication over listening, speaking, reading, seeing, and even hearing, smelling and and touching. One of the frustrations that emerged in our studies of early-career engineers is the lack of responses to their email communications. It is only later when they too become swamped with hundreds of email messages that they begin to understand that most people in large engineering enterprises cannot read, let alone respond to a large proportion of the emails they receive daily.

Of course, written assessment has been the primary assessment tool in universities for generations. However, information technology innovations over the past three decades have removed time, inconvenience and cost barriers that inhibited written communication in the past. Sending text messages and documents is now free, fast and easy. Unfortunately, there is little awareness that comprehension and trust are early casualties when leaders like engineers rely too much on written communication, undermining effective collaboration.

Routine recording of lectures in many universities and the availability of comprehensive online study notes has reduced the need for students to develop effective listening skills. In my classes, I measured the listening skills of my students to help them improve through practice to help them prepare better for engineering workplaces. After leaving formal education, it is rare for conversations to be recorded, and doing so is likely to inhibit open and frank discussions. In a work environment which depends on trusting social relationships developed face-to-face with oral communication, essential for accessing critical distributed technical expertise, prioritising written communication over face to face social interactions and attentive listening can undermine performance. In my own work experience, for example, the most valuable insights tend to be exchanged orally because of reluctance to record personal opinions in writing.

Routine lecture recording coupled with prioritising written communication can also lead to student disengagement manifesting as a reluctance to be physically present at the campus. This further undermines opportunities for students to develop effective face-to-face collaboration skills.

It is also possible to understand these education practices as a ‘hidden’ or ‘null curriculum’, because they result in learning outcomes which are not stated in the expressed curriculum (Gibbs and Simpson Citation2004, 7; Sinclair and Ghory Citation1979; Wilson Citation2006). Eisner wrote (Citation1985):

There is something of a paradox involved in writing about a curriculum that does not exist. Yet, if we are concerned with the consequences of school programs and the role of curriculum in shaping those consequences, then it seems to me that we are well advised to consider not only the explicit and implicit curricula of schools but also what schools do not teach. It is my thesis that what schools do not teach may be as important as what they do teach. I argue this position because ignorance is not simply a neutral void; it has important effects on the kinds of options one is able to consider, the alternatives that one can examine, and the perspectives from which one can view a situation or problems. (p. 97)

Indeed, the almost complete absence of engineering as it is practiced in the curriculum, not only by design, but also by the lack of faculty with extensive experience of practice beyond a research laboratory, could also be considered a null curriculum.
As generations of graduate students become engineering faculty members prioritising research publications, they tend to adopt teaching styles learned through their own years of formal education – for them recent formative experiences that are not explicitly taught. They, in turn, may be silently propagating inherited values that prioritise individual performances over collaboration, prioritise written communications over other ways of relating to people, and prioritise the technical over the social.

Academic curricula are also silent on emotions and beliefs (notions accepted without justification), yet emotions are always reflected in relationships and both influence perceptions, attitudes and behaviour. Most engineers take on informal leadership roles from the start of their careers (Blandin Citation2012; Rottmann, Sacks, and Reeve Citation2015; Trevelyan Citation2007): these silences prioritise rational logic which, through filters of emotion and beliefs, can appear completely irrational to others, eroding leadership capacity. One might even think it surprising that many graduates succeed despite these handicaps from their education.

These elements of the engineering education infrastructure, deeply embedded and reinforced, suggest that realigning engineering education with practice depends on reshaping the hidden or implied curriculum. Without this, changes to the expressed or explicit curriculum alone, no matter how extensive, may have limited effect because of the other dimensions of education infrastructure that maintain the status-quo.

It is vital to retain the technical strength of existing curricula that prepare engineers for elaboration of their technical knowledge through specialised workplace training (e.g. Jaksa, Ho, and Woodward Citation2009). While engineering and mathematics textbook practice problems have only tenuous links with real-world engineering problem-solving (Itabashi-Campbell and Gluesing Citation2013; Itabashi-Campbell, Perelli, and Gluesing Citation2011; Jonassen Citation2002; Korte, Sheppard, and Jordan Citation2008), repeated practice builds up tacit knowledge which, according to recent research findings, is how engineering science is often enacted in engineering workplaces (Goold and Devitt Citation2013). Engineers make countless rapid decisions based on tacit knowledge (Polanyi Citation1966; Trevelyan Citation2014a, Ch 5), and sometimes use specialised software embodying advanced engineering science knowledge. Only occasionally do they apply engineering science directly for themselves.

Curriculum gaps and infrastructures may be doing more than raising resistance to reform efforts. They may also be helping to create value conflicts between education and workplaces, particularly the valuing of technical over social, marginalising the influence of finance, prioritising individual performance over socialisation and collaboration, prioritising written communication and hiding social and emotional influences. The often implied, sometimes explicit association between collaboration and cheating in formal education could further reinforce this influence.

These value conflicts raise doubts about the wisdom of even attempting to educate students about engineering practice during their formal engineering education. Mason, Williams, and Cranmer (Citation2009, 24) observed

many relevant employability skills are probably best learned in workplaces rather than in classroom settings … . There may be little to be gained from universities seeking to develop skills that are best acquired (or can only be acquired) after starting employment rather than beforehand.

Workplace changes?

Some have argued for changes in the ways that firms guide young engineers (and other recruits) through their socialisation and transition to engineering practice (Korte, Brunhaver, and Sheppard Citation2015, 203). Yet organisations have their own cultural infrastructures (Buch Citation2016; Petersen Citation2015) that also inhibit changes and mask some curriculum influences. Therefore, in suggesting educational changes to enable early-career engineers to benefit from newly described engineering practice knowledge, one has to consider how such changes can fit in, rather than conflicting with formal education and workplace infrastructures.

Learning the elements of practice

Most early-career engineers learn practice by trial and error: a fortunate few have helpful mentors to guide them. Until the nineteenth century, nearly all engineering was learned this way, by experience. A few engineers such as Macquorn Rankine are known to have read original works by early scientists such as Isaac Newton's Philosophiæ Naturalis Principia Mathematica published in 1687 (MacLehose Citation1886). Engineering schools were established in seventeen century Europe to enable aspiring engineers to learn engineering science, a body of knowledge based on mathematics and physics (e.g. Conde and Massa-Esteve Citation2018). Gradually it became apparent that theories devised by mathematicians and scientists in universities enabled young people to learn faster and they avoided many of the errors that had slowed learning from experience alone. Text books were written, summarising useful theories in a way that made them easier to understand. Incorporating the original discoveries into formal education required about two centuries from the initial scientific publications.

Recent engineering practice research has demonstrated how complex workplace relationships and social performances shape technical outcomes and vice versa. The few expert engineers who have learned this by themselves help to demonstrate the potential benefits if most engineers could also acquire similar capabilities. Hopefully, future research exploring the ways that education socialisation, infrastructures, and hidden and null curricula shape students’ values and expectations can open up ways to reshape university engineering education so that students' values, practices and expectations align better with practice. We may already have sufficient knowledge to develop instruments such as concept inventories to observe such changes: even tacit knowledge can be evaluated using online surveys (Sternberg et al. Citation1995; Trevelyan and Razali Citation2011).

Eventually we might expect to see social science and humanities theories become part of the foundations for engineering curricula, a prerequisite for students to learn about the sociotechnical in their undergraduate courses. However, it took many decades to evolve todays engineering science curricula and we should not expect social theories to become an accepted part of engineering courses in less than a few decades.

There are other more immediate possibilities that could help reshape curricula. Evidence from engineering practice research shows that engineers spend much of their time on informal teaching activities (Trevelyan Citation2010a). Therefore, teaching collaborative education methods to engineering students might not only provide transferrable workplace skills, but could also enable students to assume much of the responsibility for routine teaching. Recent work has greatly increased the strength of evidence available to select appropriate education methods (Hattie Citation2012, Citation2015; Schneider and Preckel Citation2016; Smith et al. Citation2005). The roles of engineering faculty would then shift towards quality control, inspiring students and leadership.

The possibility for reshaping the hidden curriculum could depend on assessment and grading of students' teaching performances, leading and inspiring other students. Providing grades might help build a connection between rewards and collaborative work, not only from learning and using collaborative teaching methods, but also from experiences of motivating and leading others.

This is only a suggestion: there is scant evidence that arrangements like this have been developed over time in an engineering school. Naturally, it could take some time to evolve practices with productive use of time and resources, for both faculty staff and students. Engineering faculty will also need support from people who can teach education techniques to engineering students and assess their performances. The cost might be balanced against the additional time that staff will gain for research and industrial consulting activities.

Workplace interventions might also provide significant improvements. More so in advanced economies than elsewhere, early career engineers receive substantial training from specialised engineering supply companies. Suppliers provide considerable training to enable engineers to learn about their products and apply them appropriately. Education plays an important role in sales engineering (Darr Citation2002). Many engineers also undertake online-self-learning, either self-directed or through distance education providers, sometimes employer directed and at other times for personal self-development. Grafting engineering practice learning into these early-career workplace education courses might be effective, just as a small piece of an abundant fruiting variety of a tree is grafted into a less prolific sapling with strong roots.

Early career engineers are eager to expand their repertoire of technical knowledge, and tend to be resistant to 'non-technical' courses on, for example, professional skills and project management. Learning collaboration skills may immediately be perceived as non-technical as it conflicts with the technical identity developed through formal education. New labels could help young engineers see that learning about professional skills is just as beneficial as courses on wave guides, software packages and pumps. Within a course on, say pumps and variable speed electric drives, there may be opportunities to graft on elements of practice, especially if cooperative learning methods are used to situate the learning within a practice environment. Research shows that these education methods can be very effective and also require students to learn collaboration skills that echo engineering workplaces. An account of jigsaw learning and reciprocal teaching in a classroom setting reveals some remarkable parallels with engineering practice (Brown et al. Citation1993). With appropriate reflection and discussions guided by skilled instructors, any nominally technical training course could provide a rich source of experiences to reshape participants' notions of practice. Learning framed by learned collaboration, in a workplace that depends on collaboration, provides a much more fertile starting point for new notions of practice to start displacing accidentally acquired misconceptions from unavoidable gaps in formal education. Such courses will require instructors familiar with cooperative learning methods (Smith et al. Citation2005) and recently emerged research-based understandings of engineering practice. They could help participants understand the pervasive influence of finance and nurture sufficient curiosity to stimulate a journey of self-learning about other elements of practice. By drawing on accounts by participants of personal frustrations from their first months of workplace experience, instructors could refocus any technical training course around technical collaboration and other practice skills. In doing so, they could help to resolve apparent contradictions. For example the lack of response to emails and technical reports mentioned earlier, or even the apparent irrationality of workplace politics.

The same environment could also easily help participants learn the ultimate purpose of engineering, to improve productivity. Following Grinter's (Citation1955) version:

The obligations of an engineer as a servant of society involve the continual maintenance and improvement of man's material environment, within economic bounds, and the substitution of labor-saving devices for human effort.

Only a slight reframing and extension is needed today:
Engineers are people with technical knowledge and foresight who conceive, plan and organise delivery, operation and sustainment of man-made objects, processes and systems that enable productivity improvements so people can do more with less effort, time, materials, energy, uncertainty, health risk and environmental disturbances.

It would also be easy and helpful for university engineering educators to fill this noticeable curriculum gap.
For the engineers I employ, I suggest studying 5–10 pages of Trevelyan (Citation2014a) every week and writing 200–400 word reflections in their work diaries every Friday. The reflections cover workplace experiences that week that reminded them of topics in the pages they had just read, and what they had learned from those experiences, a form of metacognition. Every now and then, we supplement this with informal discussions, often following a particular incident that illustrates something they have read about.

Great expectations

The need for engineered productivity improvement is urgent.

In South Asia, for example, few engineers today learn to navigate pervasive social complexities characterising engineering workplaces in emerging economies. The result is low productivity which causes relatively high costs for engineered services and products when equivalent performance, quality, and durability is specified. The costs can exceed developed world costs by 50% to 500%, sometimes more. This is a large (and almost completely overlooked) factor inhibiting human social development: the cost of safe drinking water can be 10–20 times higher than in Australia, for example (Trevelyan Citation2013a, Citation2014a).

In the developed world, misunderstandings and inadvertently learned values contribute to the typical 33% success rate for completing large engineering projects (the record for small projects, though better, is still only 70%) (Trevelyan and Williams Citation2018a, 293–302). On 10–15% of projects, losses can approach 100% of investors' funds. As these projects rely almost completely on well-proved technical solutions, failures are almost always due to collaboration weaknesses.

So far, there seems to be no research testing a hypothesis relating acquisition of engineering practice knowledge with engineers' job performance. If we could transform young engineers' transition to their workplaces, equipping them for future challenges with research-based knowledge on engineering practice, we might all benefit immensely. There's room for plenty of innovative future research on this topic.

We need to act quickly. Some might consider it immoral to do otherwise (Heywood Citation2016).

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seemingly contradictory observations stimulated the original research on engineering practice.