WHERE'S THE VALUE IN ENGINEERING, AND IN TEACHING IT?

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ABSTRACT

New theoretical perspectives on how engineers generate economic and social value have emerged from research on engineering practice, complementing the conventional entrepreneurship emphasis on innovation and start-up enterprises. This

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research demonstrated, apparently for the first time, how most engineers generate significant economic value with limited if any opportunities for innovation, research and development in their work.

In the absence of appropriate theory, students acquire limited understanding on the contributions they will make to society as engineers. Observations from engineering practice provide a more compelling research-based narrative that could attract a more diverse student population, and help graduates secure well-paid employment.

Many engineering faculty share uneasy feelings that their students will rarely use the advanced mathematical analysis techniques taught in classes. Research explains how practice solving traditional textbook problems builds tacit knowledge that enables rapid technical decision-making in engineering practice. The research also provides insights on how typical engineering science research supports engineering practice.

We argue the benefits from widely disseminating the findings presented in this paper to help faculty staff and students better understand how they will contribute to our collective future. This can help overcome current significant engineering performance shortcomings in sustainability and productivity growth without major curriculum changes.

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1 ENGINEERING PRACTICE AND ENGINEERING VALUE GENERATION

Research on engineering practice, the work of engineers, has provided a rich body of evidence for engineering educators over the last three decades. References cited in this paper provide reasonably comprehensive coverage of research published in recent decades. For example, among many other findings, this research demonstrates that the common notion that engineers are expert technical problem-solvers needs adjusting. While solving problems will always be part of engineering practice, expert engineers aim to avoid problems by adopting systematic organizational processes and compliance with standards.

Research helps to demonstrate three complementary types of engineering activity [1] and the career roles associated with them:

1. Interact physically with artefacts and tools, mostly individually, occasionally with others;
2. Interact cognitively with abstract objects and tools, concepts and ideas, mostly using information systems; and
3. Interact with people to plan, organise, collaborate in, and coordinate type 1) and 2) activity, also advocating for and securing required finance and material resources.

In this paper, our main focus is on professional engineers who mainly specialise in type 3 activity, with periods engaged in type 2 activity and occasional type 1 activity.

Technicians develop skills and expertise mainly for type 1 activity. Many also develop aptitudes and skills for type 2 activity to support their type 1 work, and for type 3 activity as supervisors.

Technologists mainly specialise in type 2 activity, often with knowledge acquired through type 1 activity. Examples include drafters, coders, network engineers, plant operators, air traffic controllers, designers, and many others.

As they transition from education focusing mainly type 2 activity to practice that requires mainly type 3 activity, professional engineers need to rapidly acquire skills and knowledge that receive little if any attention in formal education. Many companies provide highly developed infrastructure in the form of supervision, standards, systems and work processes that support competent performance by early career engineers.

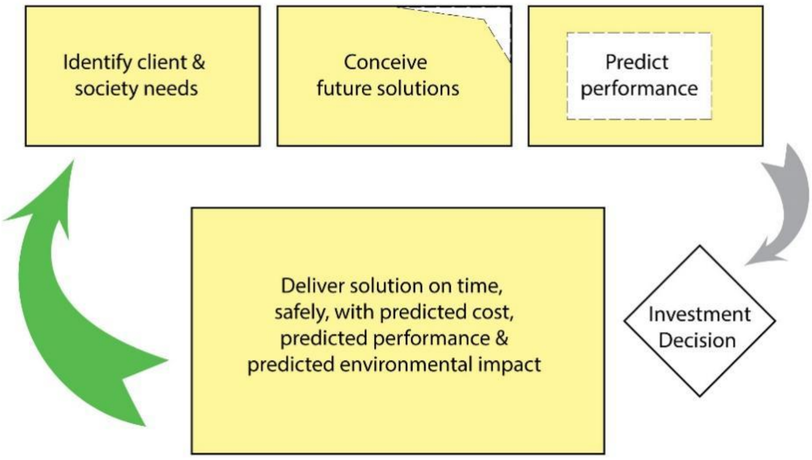

Figure 1: Sequence of engineering activities required for projects. Dashed areas in upper thread denote formal education focus [2].

Looking more closely at type 2 and type 3 activities that characterise the work of most professional engineers we see two threads shown in figure 1 [2, Ch3]. In the upper thread, engineers ascertain needs and requirements, and conceive solutions for clients in the form of engineering possibilities. They then define one or more favoured solutions and prepare plans, budgets and performance predictions to help investors raise sufficient finance. After an investment decision to proceed with the project, engineers organize procurement, delivery, implementation and operation of the required solution with the intention of meeting the anticipated performance predictions within financial and regulatory constraints. In performing this activity they acquire knowledge that improves their capacity for similar work in future, symbolised by the large arrow.

Innovation provides the principal conventional explanation for economic growth and value generation based on work by 20th century economists such as Joseph Schumpeter. This idea has led to the contemporary emphasis on entrepreneurship and start-up enterprise that often seem to attract far more interest and investment than much larger traditional firms. As a result, many educators have recently advocated entrepreneurship education for engineers.

However, both government data and ethnographic observations of engineers help to demonstrate that most engineering involves rather limited opportunities for innovation, research, and development. Nevertheless, most engineers aspire to innovative work with significant technical challenges. As one engineer exclaimed in an interview “the only two times in my entire career that I really enjoyed myself was when the client forgot to ask – has this been done before?”

In our research we observed that many engineers, perhaps most, have difficulty explaining how their work creates economic and social value [3]. This inspired a series of studies to understand how engineers generate significant economic and social value from routine activities that do not necessarily require innovation [4], complementing existing entrepreneurship models [5].

I. Engineers *create* value by differentiating products from competitors and producing plans and predictions that justify significant investment decisions to provide financial and material resources.
II. Engineers then *deliver* the potential value from these investments by engaging in highly disciplined collaborative activity. They coordinate performances by many other people, helping to ensure that original technical intentions are implemented with sufficient integrity. Mutations are inevitable as different people necessarily re-interpret technical intentions. For example, original designs are re-interpreted by construction and manufacturing firms to suit their particular expertise, along with financial, safety, environmental, regulatory and technical constraints.
III. Many engineers *protect* accumulated value through sustainment and maintenance activities. Maintaining a social licence to operate by active and supportive engagement with communities and regulatory agencies protects accumulated value created by ongoing investment in engineering operations. Investment in defence equipment provides assets that can deter or limit destructive activities by other people, again protecting accumulated value.

Reduced to the simplest possible terms, engineers generate value by conceiving and delivering artefacts that enable people to be more productive: to do more with less human effort, time, material resources, energy, uncertainty health risks, and environmental disturbances. This summary addresses sustainability as well: the need to enable the full scope of human existence while keeping well within the limits imposed by a finite planet Earth [6].

2 NEED FOR PERFORMANCE IMPROVEMENT

Historical engineering performances have been impressive in many ways, helping to emancipate and relieve billions of people from hardship, poverty and destitution. However, we now face existential threats because planet Earth cannot sustain the current rate of resource depletion, pollution and natural habitat destruction [e.g. 7].

Two significant engineering performance deficiencies compound these difficulties.

I. Most large engineering projects fail to achieve their financial objectives by a large margin and a significant proportion involve a complete write-off for investors [8, 9]. This data, available in confidence to most investors, continues to show further performance deterioration. Most projects fail because of collaboration weaknesses and overconfidence by project owners. Trevelyan [2] provides a detailed case study that illustrates how major projects can fail.

II. During the last two decades, most countries have reported significantly lower productivity growth than in the 20th century [10-12].[2] Productivity here refers to macro-economic indicators that measure the value of goods and services produced relative to labour, capital and material resources needed to produce them. This has led to stagnating or declining real incomes for many people and major political unrest in some countries. Productivity in low-income countries remains, on average, five times less than wealthy countries and this ratio has changed little in recent decades [13].

    As explained above, engineers significantly influence national productivity because productivity relies on infrastructure, tools and equipment conceived and implemented under the guidance of engineers. Yet, many engineers today do not understand the connections between their work and national productivity. Sustainability and addressing climate change rely significantly on reducing material and energy resources needed to provide goods and services, in other words, productivity improvement.

Understanding these engineering performance deficiencies can point out ways to improve engineering performances and hence sustainability.

3 INSIGHTS FROM RESEARCH FINDINGS

We argue here that applying engineering practice research findings in engineering schools could lead to significant engineering performance improvements. For example, improving the understanding by engineers on how to generate economic value could lead to improved value generation performances by engineers and productivity improvements.

We suggest that awareness on the links between engineering performances and financial outcomes has receded, as evidenced by our findings on engineers' awareness on economic value generation from their work performances. In the 1950s, this link was explicit in the definition of engineering adopted by the ASEE Grinter report [14]. Contemporary definitions of engineering make this link much less explicitly. For example, New Zealand engineers were asked to define engineering as part of a recent study by consultants to estimate the contribution of engineering

[2] See for example US Labor Productivity in Manufacturing: https://alfred.stlouisfed.org/series?seid=MPU9900063&utm_source=series_page&utm_medium=related_content&utm_term=related_resources&utm_campaign=alfred

towards that country's GDP [15]. None of the comprehensively reported engineers' responses mentioned the need for minimizing cost.

Therefore, we argue, educators have opportunities to rebuild awareness on the economic and social benefits arising from engineering and the need for performance improvements by drawing on the research we have referred to. We suggest there are three significant benefits.

3.1 Attracting more diverse student enrolment

It is well known that more women enrol in biomedical, chemical, and environmental engineering programmes [16] because they can readily appreciate the social benefits and applicability of disciplines that enact altruistic goals and values [e.g. 17, 18]. We suggest that providing a more compelling narrative for prospective students that explicitly engineering with its social and economic benefits in terms of enabling people to do more with less effort, resources, health risks and environmental disturbance may help to attract more women and students from diverse backgrounds into other engineering disciplines.

3.2 Improving graduates' career outcomes

We suggest that graduates who have a clear understanding on how their work creates economic value for firms and social value for communities are more likely to provide benefits for their employers. In the long run, these graduates may attract higher remuneration in recognition of the value they provide for their employers, in accordance with the marginal revenue productivity theory of wages in labour market economics [19].

3.3 Faculty motivation

Many engineering faculty staff experience identity conflicts and an unease that few students will ever directly apply the knowledge they acquire in engineering science and mathematics classes [20-23].

Recent work on how mathematics is used in engineering practice could provide reassurance. While it is true that engineers rarely apply the methods they learned in class directly, they often make instinctive decisions based on that knowledge. In other words, they acquire substantial tacit knowledge from solving numerous textbook problems which helps them make rapid strategic decisions that rely on knowledge of mathematics and engineering science [24]. Furthermore, many engineers rely on software that incorporates advanced techniques, often far beyond those learned in school, so they apply classroom knowledge indirectly, without necessarily being aware that they are doing so. That is the nature of tacit and embodied knowledge: it is knowledge that one is mostly unaware of [25].

Faculty staff can gain further reassurance by understanding that engineering science research builds knowledge that finds its way into practice through software, data libraries, standards and sometimes new technologies and products. All these contributions enable more accurate performance predictions, faster diagnoses and more reliable artefacts and materials, generating considerable value in the hands of engineers. Again, practicing engineers are not necessarily aware of all the knowledge embodied in the products and software they use in their work.

4 SUGGESTIONS FOR ACTION

Despite more than two decades in which graduated competencies have shaped engineering education, the gaps between education and practice remain, and graduates are surprised by the emphasis on type 3 activity when they start work [26]. While many would argue that education can never provide a complete preparation for practice, overcoming significant engineering performance deficiencies outlined in this paper requires urgent actions.

We first suggest that engineering schools help students learn from research-based explanations on how they will contribute economic and social value as engineers as outlined in this paper. This can help rebuild awareness on the critical nexus between technical engineering and economics [5]. This could be reinforced by helping faculty staff understand how their work contributes economic and social benefits, so that they can, in turn, better inform students on how their classroom learning will contribute to practice. Accordingly, we advocate substituting commonly repeated explanations with research-based explanations provided in this paper and the cited references.

For example, the common notion that ‘engineers are expert problem-solvers’ is only partly true, as explained above, and fails to distinguish engineers from many other occupations in which practitioners use their expertise to solve problems. We advocate using research-based explanations specific to engineering such as delivering artefacts and systems that enable other people to be more productive with less effort, time, materials, energy, health risks, uncertainty and environmental disturbance are specific to engineering.

We also suggest that engineering schools ensure that students are aware of significant contemporary engineering performance deficiencies as outlined in this paper. Students also need to know that they can contribute to performance improvements through their work, at the same time improving productivity and sustainability.

In engineering schools with entrepreneurship courses, we suggest complementing material on innovation and start-up businesses with explanations on how engineers also create social and economic value through routine, everyday engineering that does not involve innovation.

We further suggest that educators work at reducing the many misunderstandings on engineering practice that have arisen because there has historically been little understanding of practice among faculty staff. Trevelyan [2] lists around 100 such misunderstandings.

We suggest that engineering schools encourage collaborative pedagogies [e.g. 27] with known educational benefits in order to better prepare students for the collaborative type 3 activity that characterizes most engineering practice.

We suggest that all of these actions could be achieved without significant curriculum changes. The authors are happy to help engineering schools implement these suggestions.

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6 DISCLOSURE STATEMENT

No conflict of interest was reported by the authors.

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