Submission to Productivity Commission, August 2025

Comments on the interim report

"Building a skilled and adaptable workforce"

Engineers and productivity in Australia

Emeritus Professor James Trevelyan

The University of Western Australia, Nedlands 6009.

E-mail: james.trevelyan@uwa.edu.au

Tel: +61 402 481 167

Summary

This submission represents my personal opinions based on my engineering research and practice career since the 1970s. While I am a member of Engineers Australia, and Emeritus Professor at The University of Western Australia, this submission does not represent the views of either organisation.

This submission addresses section 2 of the interim report *Building a skilled and adaptable workforce* and points out the need for improving the post-graduation workplace education of engineers. There was no mention of this need in the interim report.

Engineers are key actors influencing productivity in Australia. Engineers conceive, deliver, operate and sustain products, infrastructure and systems that enable ordinary Australians to be productive.

There are two significant engineering performance issues in Australia imposing significant avoidable costs on government, private firms and the community.

1. Large and small engineering projects are failing to meet investor expectations, causing large losses for Australian companies and governments amounting to at least AUD 50 billion annually. These failures arise partly because they remain hidden by their owners so engineers cannot learn from past mistakes, partly because of collaboration weaknesses, and partly because most engineers have only a weak understanding on how their work contributes economic and social value. Apart from the financial impacts, these failures are also delaying our energy transition from fossil fuels to renewables.
2. Performances on routine engineering work such as maintenance show similarly large opportunities for improvement. UK and Scandinavian research has observed that even in large and well-organized companies, operating and maintenance mistakes contribute opportunity costs up to 50% of reported turnover. The core issues lie with the interactions between people, mediated by computer information systems.

Both issues have significant productivity impacts. The immense costs are potentially avoidable. Even a 10% reduction in losses would be a significant productivity boost.

Neither engineers nor engineering have been mentioned in Australian Productivity Commission reports since the mid-1990s. It seems that the significance of engineering as an influence on Australian productivity has been overlooked in the past few decades. Perhaps the magnitude of the issues I have raised will help to change that.

In the detailed submission, I explain why significantly improved workplace education could help engineers learn how to avoid these costs. Currently, there is limited effective feedback of project and engineering practice failures and shortcomings, so it is not surprising that there is no performance improvement.

Policies that incentivise firms to invest more in workplace education for engineers could lift performance standards and might help avoid many of these costly failures.

In this submission, I argue that the most effective policy change would be to introduce a national engineering registration agency (NERA) for engineering firms. Firms would be reviewed and awarded ratings indicating their financial strength, discipline expertise, engineering capability development and training, strength of their systems, processes and procedures, and quality management. Initially it would likely be voluntary for all except firms involved in work posing large safety hazards such as apartment buildings over a certain height, major energy and chemical plants, nuclear installations, tunnelling, large underground or open cut mines, facilities with bio-hazards, etc. As the agency demonstrates its benefits, registration requirements might be widened. Alternatively, if the benefits are substantial, there might be no need to widen registration requirements because firms would seek a ratings audit as part of their business development.

Engineering professional societies would continue with certifications such as Chartered Engineer and EngExec because these qualifications would contribute towards the ratings for engineering firms. However, the current state-based registration of individual engineers could be phased out over time, also providing a minor productivity improvement.

A further policy suggestion is to require government agencies commissioning major engineering work costing more than $500 million to engage appropriately qualified consultants to review project plans before final investment decisions are authorised, and also to perform detailed evaluation studies on the projects and their outcomes 12 months or more after completion. The results of these evaluations should be made available to the federal agency responsible for registering engineering firms so the knowledge gained can inform workplace education for engineers.

In this submission I explain why this national approach could be effective, and why the current state-based registration schemes are not fit for their intended purposes.

TABLE OF CONTENTS

1 Background knowledge

In making this submission, I will draw on 25 years of research on engineering practices, five decades of personal experience practicing engineering, and 18 years commercializing an air-conditioning innovation with global markets. Some of the research findings provide insights beyond engineering practice. My commercialization experience points to opportunities to improve government incentives to promote innovation activity in the economy.

I have practised as an engineer since 1971, and between 1975 and 2016 I taught engineering at The University of Western Australia. I continue to practise engineering, directing a start-up company commercialising my air-conditioning invention, and selling our products in more than 30 countries world-wide. Between 1975 and 1992, I led the team developing sheep shearing robots at the University of Western Australia. This project established Australia as a recognized world leader in robotics research. Subsequently, with research students, we demonstrated remote control of industrial robots using the internet, one of the earliest demonstrations of the internet of things.

Through my career, I have also helped direct family investment portfolios in Australia, the UK and Europe, giving me an insight into the world of investment finance.

With my students, I researched engineering practices in several countries from 2001 onwards. We accumulated what is now widely acknowledged as one of the world's largest collections of knowledge on engineers and how they perform their work. As an emeritus professor, I continue to write research papers, books and give talks at many conferences about our discoveries. My publications have achieved some of the highest citation counts in what is still a small and emerging field of research.

The research evidence base includes over three hundred qualitative interviews with engineers in Australia, India, Pakistan, Singapore and Brunei. A dozen field observation studies, surveys of hundreds of engineers, and collaborative research with universities in USA, UK, Germany and Portugal have provided additional corroborating evidence. In part inspired by our research, several international research teams are extending our collective understanding about engineering and how it is practised in many different countries and settings. So far, all of these publications have provided findings corroborating our own findings.

In 2011, I assisted Engineers Australia to write the Stage 2 Competencies for Professional Engineers. These form the core qualification criteria for Chartered Engineer status which is accepted as the main qualification for registration as an engineer in Queensland (RPEQ). Other states have adapted these qualifications for their own registration schemes.

Nearly 15 years later, continuing research has shown that we need to improve on these qualification requirements.

In this report, I have provided only key reference citations. Many others can be provided on request.

2 Opportunities to improve national productivity

Two economic measures reflect productivity. Labour productivity measures the value of goods produced divided by the number of hours worked. Multi-factor productivity measures the value of goods produced divided by the value of capital, energy, materials, purchased components and labour needed to produce them.

Engineering activities strongly influence both measures. Labour-saving devices, automation, energy-efficient plant, infrastructure, telecommunication systems all help to decrease the labour, energy, time and materials needed to produce goods, increasing labour and multi-factor productivity. Reducing uncertainty, health risks and environmental disturbances also reduce wasted investment and societal costs.

There is wide agreement that future economic prosperity and social development in Australia depends on productivity improvement. After significant growth through the 20th century, productivity growth has slowed significantly, both in Australia and other countries. Economists have debated the underlying causes.[1] Advocates for productivity improvement in the business and finance communities, and the Australian Productivity Commission have argued strongly for lighter regulation and more flexibility to deploy labour more effectively.

In this submission, I argue that there are large opportunities for productivity gains by introducing policy reforms and incentives for improved performances by engineers.

In a separate submission, I have argued that there are further opportunities for productivity gains by providing additional assistance for innovators, particularly in non-IT industries.

Our relatively narrow economic base and reliance on primary industries – agriculture and mining – constrain opportunities for national productivity improvements. We have an extraordinary opportunity to benefit from our geographic location, in the same region as the largest concentrations of people on the planet. Our nearest neighbour, Indonesia, has a similar population to the USA and offers immense market opportunities. Across southern Asia, there are nearly three billion people, similar to the combined populations of China, Europe and North America. However, we have singularly isolated ourselves from these opportunities by allowing our innovation sector to focus mainly on information technology, an industry in which most of our neighbours also excel and compete. We have chosen to ignore much greater opportunities that could be tapped by offering physical products that meet the needs of huge nearby populations. However, we need improved performance by Australian engineers to take advantage of these opportunities.

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[1] See for example (Manyika et al., 2015; Remes et al., 2018)

3 Engineering influences productivity

Unfortunately, the contributions of engineering in productivity growth have not been well understood, aside from technological innovation. Innovation accounts for only a small proportion of all engineering activity in the economy. Most engineering activity, around 97% by recent estimates, comprises routine, ordinary, everyday, non-innovative work. [2] Until recently, there has not been a theoretical understanding on how routine engineering activities contribute to economic and social value generation. This gap limits the ability of engineers and businesses to gain economic value from engineering and helps to explain the current appalling delivery performances on large engineering projects.

Bridge building is one such routine engineering activity. Fortunately, very few bridges suffer serious failures. That reflects the attention given in educating civil and structural engineers to develop their capabilities to understand how to make the best use of structural materials in bridge design.

Contrast this with delivery performances on large engineering projects. On average, for every six projects costing more than USD 1 billion, only two will provide better than half the financial return promised to investors when the expenditure was approved. One will be a complete loss: the investors will lose all their funds. The other three will run significantly over the planned budget and time schedule, and will provide only a fraction of the forecast economic benefits when they were approved.[3] These project failures are not the results of innovation: large projects almost invariably rely on well-established technologies and construction methods. Unfortunately, these performance statistics are gradually worsening with time. Australia is better than the international average, but only slightly.[4]

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[2] (Trevelyan & Williams, 2018) examined data on R&D spending and other sources to arrive at this estimate.

[3] Research interviews with bankers revealed that they typically discount predicted financial returns on engineering projects by 50%.

[4] IPA Global Inc (formerly Independent Project Analysis), widely respected internationally, has provided outline data on private sector project completion performance in Australia and other countries, based on data from about 25,000 projects. Unfortunately, governments prefer to avoid engaging with IPA or similar firms because they are reluctant to have their project performances scrutinized in depth. However, Bernt Flyvbjerg at Oxford

Crucially, for Australia right now, the current transition from fossil fuel energy production to renewables is being delayed and is costing more than it should because of difficulties with completing engineering projects on time, with predicted performance.

If bridges, ships, cars or aircraft were failing at these rates, there would be a national outcry and public inquiries to determine causes and solutions, both technical and policy improvements.

However, the directors of companies that own these failing engineering projects do not want the results publicized, fearing sanctions from their shareholders. Therefore, there are only muted discussion in meetings discussing project management and there are few if any opportunities for engineers to learn from these mistakes. The lack of performance improvement is not surprising. Most engineers working on these projects only see a relatively narrow aspect and may not even be aware that the project has not met the owner's or investor's expectations. The Australian community bears the cost, perhaps as much as AUD 50 billion annually, through inferior performance of investing entities and owner firms in Australia. Many form significant components of superannuation funds. Similar losses arise from operating and maintenance mistakes in major industries: again the owners avoid drawing attention to these issues in their annual reports.

If we could devote similar attention to educating engineers to avoid such financially catastrophic failures as we allocate today to understanding bridge-building materials and their limitations, we could reasonably expect fewer project failures, and large cost savings and productivity improvements for the Australian community. Improving completion performance on engineering projects has the potential to save governments and companies billions of dollars annually.

University has accumulated similar data from about 15,000 projects that includes public sector projects. Public sector projects tend to have a worse record that private sector projects because they are vulnerable to shifting political priorities.

[4] (Flyvbjerg, 2014; Merrow, 2011; O'Brien, 2009; Young, 2012)

There is no evidence that Australian engineers perform significantly better or worse than engineers in other developed countries. Other countries face similar issues, so opportunities for performance improvements extend world-wide. Effective solutions might offer a substantial export opportunity for Australian engineering firms.

4 How much do these performance weaknesses cost?

As I explained earlier, losses in major private sector engineering projects are likely to be costing Australia at least AUD 50 billion annually. This figure can be roughly estimated by adding the cost of all engineering projects initiated annually, around AUD 140 billion last year in Australia. The economic benefits must have been more than sufficient to cover the original investments since there are few significant engineering projects that are not justified by some form of economic benefit exceeding the cost. Let's conservatively assume that the forecast benefits from all these projects exceeded the cost by 50% over time, giving a total expected benefit of AUD 210 billion. Approximately one in six projects result in total losses. That's around AUD 23 billion lost, and a further AUD 12 billion in opportunity costs. Given that 2/3 of the projects provide less than 50% of the anticipated return on investment, we can estimate a further opportunity cost of about AUD 23 billion. These performance statistics are only based on private sector projects: government projects perform significantly worse, but government agencies resist performance evaluation. Even though smaller projects do perform better than larger projects, the losses likely exceed AUD 50 billion annually.

Opportunity costs from operating and maintenance costs on existing engineering plants, factories, mines, offshore assets, ships, aircraft, fleets of trucks, bridges, tunnels, hospitals, telecommunication systems... are harder to estimate. Knowing that earlier research suggests up to 50% of reported turnover, we can safely assume that these opportunity costs are at least comparable to the cost of project failures.

The total from both types of loss likely exceeds 100 billion annually, or nearly 4% of Australia's GDP, USD 1.73 trillion. Even a 10% reduction in these losses would contribute significant additional productivity growth.

5 What are the factors causing these losses?

Like all engineering failures, there are likely to be multiple intersecting contributory causes, and we don't have sufficient knowledge even to identify their relative significance. However, all point to the need to improve post-graduation workplace education for engineers.

5.1 Collaboration and organisation weaknesses

The largest group of contributing factors involve collaboration or organisation weaknesses, often labelled as communication failures. For example, one of the leading causes of project failures is divergent understandings on the project objectives between the project owners and the firms performing the work.

University engineering courses do not teach engineering students how to collaborate effectively, let alone how engineering organisations work. Few if any students learn about contemporary process safety approaches. Faculty often organise students into groups to complete major assignments or "group projects" and assume that the students are collaborating, even though there is no teaching on how to collaborate effectively. Research shows that this faculty assumption is mistaken. Collaboration in university courses is regarded by many as a form of cheating. Students will often echo lecturers' expectations, saying something like "well, surely, one is supposed to learn for oneself." Many have argued for explicit teaching of collaboration, and interventions known to improve learning outcomes include teaching and assessment by student peers. Unfortunately, explicit teaching of collaboration, for example by institutionalized teaching and assessment by student peers, is not widely valued or practiced by faculty today. While engineering schools expect students to work in teams for assigned projects, they do not formally teach collaboration, and expect students to acquire collaboration skills by practice alone. Education research tells us, of course, that practice alone reinforces counter-productive behaviour as much as productive behaviour, and that counter-productive collaboration behaviours extend into the workplace.[5]

Most major industrial plant failures have been shown to originate with organisation weaknesses, even though the initial tendency has been to point to technical reasons. A recent Australian example was the explosion at the Callide power station. The owners offered detailed technical explanations in an apparent attempt to focus attention away from persistent organisation failures.[6]

Here it is important to understand that collaboration in engineering practice is much more complex than students collaborating (or otherwise) in group projects, especially in large organisations. Engineers have been developing specialized collaboration and organisation methods for millennia, and many ancient techniques are still used today. Take engineering models, for example. These are not just decorative accompaniments for technical documents: they are engineers' representations of the finished product to enable their intentions to be understood by others. Today, most models are 3-D visualizations on computer screens. However, these alone are meaningless without accompanying technical specifications and inspection and test plans.

Currently, most engineers learn these collaboration methods largely through experience and by trial and error and being exposed to them by chance. Few if any engineering graduates know anything about engineering organisations, specifications, inspection and test plans, configuration management and control, change management or quality management. These are just a few of the elaborate formal collaboration methods used in engineering firms. Beyond those are many informal collaboration methods, some of which have been studied by engineering practice researchers.[7] It would be unusual for any faculty in university engineering schools to be aware of these methods and how they are used in industrial

[5] (Leonardi, Jackson, & Diwan, 2009; Sheppard, Macatangay, Colby, & Sullivan, 2009)

[6] (Brady, 2024)

[7] E.g. (Anderson, Courter, McGlamery, Nathans-Kelly, & Nicometo, 2010; Blandin, 2012; Trevelyan, 2010; Vinck, 2003)

practice. Many engineers gain only a passing awareness of such methods. Therefore, it is not surprising that so many projects fail due to inadequate application or implementation of known collaboration methods developed over many decades by engineering firms.

In my early engineering career, I was fortunate to be exposed to many of these methods, but I did not understand their significance at the time. It was only when I started researching engineering practice, and encountered so many engineers who had never been exposed to these methods, that I realized how fortunate I had been in my early career choices.

5.2 Error checking weaknesses

Another contributing factor to project failures, particularly schedule and budget overruns, is weak review and checking processes. In our research, we discovered entirely by accident that engineering review and checking processes are often ineffective.

Our research has demonstrated that, even on large projects with formal auditing of design checking processes, engineers eschew detailed checking work, either delegating the work to junior colleagues, or avoiding it altogether, while signing formal documents to state that they have checked them.[8] A later section Design checking weaknesses describes how we discovered this. We later discovered that this weakness can be attributed to a weak understanding among engineers on how their work generates commercial value. Engineers that we interviewed saw checking work as impeding "productive design" and adding to costs, also delaying completion. They did not appreciate how checking generates economic value by reducing the cost of later corrective work on site (which is much more expensive and causes completion delays), and also by providing investors with greater assurance that commercial and technical risks have been thoroughly investigated.

There have been many instances in engineering where engineers have overlooked detailed checking because of commercial pressures. This may be inadvertent: with limited time, engineers may direct their primary attention at immediate commercial issues. However, this can also be deliberate. In an admittedly extreme instance, the Volkswagen diesel cheat device

[8] (Trevelyan, 2010)

case illustrates how powerful organisation influences motivated hundreds of engineers in different firms to simultaneously engage in deliberately deceptive practices.[9] Australian transport infrastructure projects such as the cross-city east-west tunnel under the Sydney central business district have provided some very poor results for investors, in part because engineers were pressured to inflate traffic forecasts. This deception was considered necessary to make financial forecasts sufficiently attractive to secure the necessary investments.

The consequences of error checking weaknesses include project delays and uncontrollable cost increases because it is much more costly to rectify mistakes later in an engineering project. In fact, the first company where we discovered weaknesses in design checking actually wanted us to tell them why so many of their projects were running late with unexpected cost increases.

5.3 Front end loading weaknesses

Another leading cause of project failures is insufficiently detailed planning and investigations before the final investment decision. Spending on detailed design, planning, prototype testing and other investigations is often referred to as front end loading.[10] For example, subsurface investigations by drilling are particularly important for tunnelling or mining projects. Time after time, unexpected ground conditions have confounded tunnelling projects because insufficient drill holes were sunk to investigate ground conditions. A recent Australian instance was the flooding of tunnel boring machines on the Snowy 2 pumped storage project. But this is only one aspect of the "front end" planning and investigations needed to minimize the risk of project failure. Another aspect is securing access to project sites, securing approvals well in advance of work commencing, and engaging local communities with the aim of building a social licence to operate, community trust and confidence, something that takes time to develop. The data shows that reducing front-end loading significantly increases the risk of project failure.

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[9] (Castille & Fultz, 2018; Contag et al., 2017; Mansouri, 2016)

[10] (Flyvbjerg, 2014; Flyvbjerg & Gardner, 2023; Flyvbjerg & Kao, 2014)

5.4 Unrealistic objectives

Another contributing cause of project failures is unrealistic time and schedule and cost expectations that fail to take into account the results of detailed engineering assessments. In our research, engineers have told us how they would be expected to work with budget cuts exceeding 20% and unrealistic completion deadlines. When engineers have pushed back on these requirements, their managers have tended to accuse them of "gold plating", in other words, being excessively cautious with their designs and schedules. A significant difficulty for engineers in this position is that most lack an appropriate background commercial appreciation or even a vocabulary to explain the risks and consequences in meaningful terms for senior decision-makers. Decision makers may respond by suggesting that engineers "cannot see the bigger picture" or "understand the commercial imperatives".

IPA and other firms provide an assessment of likely project outcomes to project owners before they make their final investment decisions. One of the firm's employees responsible for giving project owners bad news told me that he made extensive use of an artist's impression of the sinking *Titanic*. "This is your project," he would tell them. What is remarkable, and concerning, is that many project owners persist with projects that were forecast to fail, without making appropriate adjustments.

Here we see an example of confirmation bias, the tendency of human decision-makers to take less notice of information that conflicts with their expectations and intentions. Yet I have not come across a single instance where engineering students are taught about this in engineering schools.

5.5 A management issue?

Many engineers dismiss these findings on project completion failures as "management issues" while failing to acknowledge that crucial decisions are made by highly experienced engineers. Some engineers see the problem in terms of unrealistic budget and timescale requirements imposed by project owners, or even senior managers of engineering firms who have under-priced their work packages in order to secure contracts from the project owners.

Our current poor project delivery performance statistics seem to be well understood, at least in some board rooms, and the failures are often blamed on engineers. In one interview, a banker told me "we just halve the engineers' investment forecasts". My research interviews with CEOs and senior investment advisors revealed a disdain for engineers, with comments such as "Engineers frustrate me immensely: they just don't understand the basics of running a business." A small business owner informed me "I just sacked all but one of my engineers." Another CEO, dependent on the work of tens of thousands of engineers, told me "Whenever I find an engineer in my organisation, I sack them on the spot."

Such attitudes, arising from the poor performances of engineers, are clearly counter-productive and point to the need for change. The relevant question is what kinds of changes are needed?

One of the obstacles is the tendency among engineers to view any "non-technical" issue as "not real engineering" and therefore a management issue. One of the aims of my research and my publications has been to argue that work that is apparently non-technical for engineers usually depends on awareness of technical constraints, and is therefore an engineering responsibility. In other words, engineers could gain much by acknowledging that all of their work is "real engineering" and that real engineering is much more than the technical that they associate with engineering school teaching.

IPA Global has started short courses on how to plan projects to avoid the issues described above. So far, I am unaware of performance improvements resulting from these courses, but they are a small step in the right direction.

5.6 We are not learning from project failures

When projects fail to provide the expected returns for the owners, there is usually no publicity. Mostly, owners prefer to remain silent. When very large project failures have occurred, some shareholders have asked for inquiries.

BHP conducted one such enquiry after the failure of the Boodarie Iron (formerly known as HBI, hot briquetted iron) project in Port Hedland. The company inquiry reported "significant knowledge improvement in materials science". The real organizational causes of the project were never disclosed, even within BHP as far as I can tell from first-hand accounts provided to me.[11] There were multiple causes, including a decision not to build a pilot plant first, and a decision to proceed with the simultaneous construction of four full-scale plants rather than serially, learning and passing on lessons from one to the next. Locating the plant in Port Hedland, a remote and isolated town at the time, made it difficult to attract and impossible to retain engineers with sufficient experience on similar projects requiring knowledge of high temperature, high pressure processes with explosive gases and solid powders. BHP itself had no prior experience of such processes. The mining arm of the company only had knowledge of handling rocks at normal temperatures. Even to this day, the lessons of that project are not available to engineering students.

What we see is a culture of suppressing learning from failure. It is no surprise, therefore, that project delivery performances continue to decline. There is also a consistent patten where failures are attributed to technical unknowns, when the root cause of failure is collaboration weakness such as failure to effectively share knowledge with people who need it.[12]

6 Ill-conceived attempts to overcome practice failures

The Opal Towers failure, [13] along with other construction industry failures, led to widespread dissatisfaction from both high rise apartment residents and investors. Pressure from these interest groups provoked the New South Wales state government to introduce a registration scheme for engineers in the building industry. These failures are relatively minor in terms of dollar costs compared with major project failures in Australia and internationally, but became major issues attracting political attention.

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[11] Available on request, to be treated in confidence.

[12] See for example, reports on the Callide generator explosion in Queensland. The owners have made extensive efforts to pin the blame on technical factors, to avoid confronting organization failures (Brady, 2024).

[13] (Hoffman, Carter, & Foster, 2019)

The intention was to ensure that engineers have sufficient proficiency to ensure public safety and reasonable investment returns for investors. Other state governments, following the New South Wales lead, have since introduced registration schemes for engineers working in the building and some other industries.

Today, the Engineers Australia chartered engineer qualification serves as the "gold standard" for recognizing the capacity of engineers for independent, unsupervised practice. It is based on evidence of supervised work experience over several years, as well as the engineer's original university qualification. Chartered status provides near-automatic recognition for the state-based engineering registration schemes.

The oldest scheme for registration of professional engineers in Australia is the Queensland process leading to Registered Professional Engineer Queensland certification (RPEQ). To gain RPEQ, an engineer needs a formal qualification (e.g. a Bachelor of Engineering degree) and several years of supervised experience in a particular area of practice, such as civil engineering construction, structural design, fire safety engineering, mechanical building services, and many others. Engineers Australia lists many current areas of practice. Registration is contingent on demonstrating proficiency in a restricted set of the Engineers Australia Stage 2 Competency Requirements for Engineers.[14] There are several pathways to gain RPEQ registration offered by engineering professional organizations such as Engineers Australia and Professions Australia.

The Australian Capital Territory requires all civil, electrical, fire safety, mechanical, and structural engineers to be registered. Similar provisions apply in Victoria.

In New South Wales, registration is only required for engineers working on certain classes of buildings – multi-storey apartment buildings, hotels, hostels and residential buildings housing people who require assistance. There are similar provisions in Tasmania and the Northern Territory.

[14] 1. Dealing with ethical issues, 2. Practice competently, 4. Develop safe and sustainable solutions, 6. Identify, assess and manage risks, 13. Engineering knowledge (e.g. relevant standards).

In Western Australia, only civil, fire safety, mechanical, and structural engineers working in the building industry need to be registered. The Western Australian scheme is the only one that requires engineering firms to be registered.[15]

Therefore, as with the early days of railways in Australia, each state has instituted a different regulation scheme. While there are some provisions for mutual recognition of qualifications, registration may be required in every state where and engineer intends to work, except South Australia.

6.1 Registration cannot guarantee performance or avoid future failures

Unfortunately. registration for engineers is no guarantee of performance.

Explaining how to avoid similar failures in future, the Opal Towers report[16] highlighted the need for independent, third party review of designs and changes, and on-site checking by an appropriately qualified engineer. Surprisingly, even in the USA with some of the world's most rigorous licencing requirements, there is still no formal requirement to adopt practices such as independent third party reviews, one of the main learnings from the 1981 Hyatt Regency collapse in the USA.[17]

The Stage 2 Competency Requirements for Engineers *do not require* engineers to adopt this practice. In a recent submission to Engineers Australia, I have drawn attention to the need to strengthen the requirements to have designs, modifications and on-site work checked by competent engineers in a new revision of these competency requirements.

However, even if competency definitions were modified to include these requirements, registration would still would not fully address the performance issue.

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[15] https://www.wa.gov.au/government/multi-step-guides/building-engineering-registration/building-engineering-practitioner-registration-new

[16] (Hoffman et al., 2019)

[17] (Luth, 2000; Moncarz & Taylor, 2000)

As described earlier, our research has demonstrated that, even on large projects with formal auditing of design checking processes, engineers avoid detailed checking work or delegate the work to junior colleagues.

Most of the different state registration schemes do not cover many areas of engineering which have significant community and workplace safety implications. For example, software engineers work on nuclear reactor safety systems which, these days, rely on extensive software systems to gather data from sensors, analyse the data, and either control reactors automatically or provide advice to manual operators. Failure of these systems could have catastrophic consequences. The Callide power station explosion,[18] might conceivably have resulted in such a catastrophe had the power source been nuclear instead of a conventional boiler. There are hundreds of chemical plants around Australia relying on software control systems, any of which could fail with serious consequences for nearby communities and likely the employees. Yet, the engineers who design and implement these systems are, with the exception of Queensland, not included in state registration schemes.

From this discussion, we can conclude that the current registration system is not able to provide any strong measure to maintain practice standards and protection of public safety. The schemes are cumbersome to administer, require time, effort and payments from engineers, yet are not fit for purpose. None of the schemes requires engineers to be sufficiently proficient to be able to contribute to improving national productivity, the subject of this submission.

The Queensland registration system dates back to 1929. As far as I can ascertain, searching with perplexity.ai, there have been very few instances when Queensland engineers have been sanctioned.[19] It is difficult to accept that every other engineer in Queensland has maintained unquestionable standards of practice over nearly a century. A scheme that does not regularly sanction engineers for sub-standard practice cannot be considered to be effective in

[18] (Brady, 2024)

[19] I have received informal feedback indicating that several hundred engineers have faced some form of disciplinary proceedings under the Queensland registration scheme, however there is no public information about these proceedings or the results.

maintaining practice standards. In contrast, hundreds of Australian doctors face disciplinary proceedings around Australia every year.[20]

Unfortunately, the available evidence demonstrates that professional registration, as currently implemented, cannot improve engineering performance standards, nor avoid the kinds of failures that motivated governments to introduce registration schemes.

- There is no stated requirement in any of the registration schemes for engineers to have work reviewed by independent experts if it has serious safety implications, a practice recommended on many occasions by investigations into major engineering failures.
- Research evidence demonstrates that peer review processes designed to detect and correct mistakes in engineering work are not effective. This factor is a major contributor to cost and schedule overruns in large engineering projects reported above.
- There is scant public evidence, even from the Queensland scheme which has been operating for nearly a century, that engineers who fail to meet reasonable performance standards are facing sanctions or losing their professional registration.
- Many engineers working on safety critical systems are not required to register with state schemes.
- Firms and their culture, systems and procedures have a much larger influence on engineering performance standards than individual competency attributes. Engineers with professional registration will find ways to cut corners when commercial pressures force firms to economize.

In this submission, I suggest an alternative approach that could improve engineers performances, and also overcome the difficulties briefly described above. However, there is one further weakness in the current schemes that needs to be addressed.

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[20] While the proportion of engineers facing some kind of sanction for failing to meet accepted performance standards in the USA is believed to be small, substantially less than 1 in 1,000, the few engineering registration boards that report such cases demonstrate that there is some level of effective enforcement. For physicians the rate is about 1 in 1,000. (Perplexity.ai, 11th July 2025, https://www.perplexity.ai/search/what-proportion-of-engineers-a-sVWcD88qRLOc.0OoS42Wnw#0) Similar figures apply to European countries.

6.2 Upgrading engineering qualification requirements is difficult

Engineers Australia is aware that the current Stage 2 Competencies for Professional Engineers document needs to be updated with stronger requirements for design review, sustainability and resilience to future climate changes and other improvements.

However, the government staff administering the engineering registration schemes have limited understanding of engineering practices, and also have a challenging set of expectations to meet from their departmental heads. Engineers Australia is only one of several engineering certifying organisations.

The literature on government regulation of professions reveals the complex intersections of interests among professional organisations, legislators, regulators, courts and the community at large.[21] Some professional societies push for tighter regulation in response to members demands for exclusivity, aiming to protect what might be a total or partial monopoly on services. Other professional societies push for lighter regulation, wanting to make their career and membership pathways more attractive for a greater number of people. Governments and courts can find themselves caught in the middle of these contests with no easy resolution except to maintain the status quo. The difficulties now being encountered by Engineers Australia echo similar contents extending over the past 120 years in other countries.

Therefore, even if the need to improve professional competency standards becomes apparent, it is difficult to persuade state-based regulators to tighten their regulatory requirements.

7 Can workplace learning fill the knowledge gaps?

So far, I have argued that engineering performance weaknesses are imposing significant costs on the Australian community that could, at least in part, be avoided if engineers have opportunities to learn how. However, our present workplace education pathways are inadequate, and fail to address the knowledge gaps needed to overcome project failure issues discussed earlier.

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[21] (Law & Sukkoo, 2005; Robinson, 2018)

Before suggesting ways to improve education opportunities for engineers, I need to explain why engineers need at least four years of post-graduation learning to be able to practice without supervision.

Today, this is a largely informal process, unlike the medical profession that formalizes post graduation education as a series of examinations, qualifications and college memberships gained by specialist physicians.

In my research I identified over 200 generic engineering activities performed by engineers in practically all disciplines in the first few years of practice, none of which are covered or even introduced in university engineering degree courses. Most are not explicitly mentioned in current professional competency requirements.[22]

The reason for this lack of curriculum coverage is partly because engineering faculty in universities are recruited mainly for their academic research capacity, and to a lesser extent their undergraduate teaching capacity. Another reason is that non-technical, generic activities are typically not recognized by engineers as "real engineering work".

Surveys have shown that few if any university engineering teaching staff have recent experience of commercial engineering practice. If they do, it is almost always in a research and development or specialist technical capacity with no significant commercial responsibility. This is not unique to Australia: it is characteristic of universities world-wide. The loss of practice knowledge in engineering faculties has accelerated since universities have been ranked primarily on their research reputations.

Therefore, there is a need for engineering firms to develop the post-graduation proficiency of their engineers.

Until the 1980s, in Australia and other countries, the need for post-graduation workplace education was primarily met by public sector engineering institutions. Engineers learned basic concepts such as specifications, inspection procedures, contracts and, above all, the need to

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[22] A full list appears in the Supplement

implement solutions with the least possible cost and uncertainties. Most engineering was performed in the public sector in Australia until the latter half of the 20^{th} century. In such an environment, private engineering firms could recruit experienced engineers from the public "pool" as and when needed. Therefore, there has been no long-established tradition in Australia for private firms to develop the proficiency of their engineers. This is reflected in the often-echoed call for universities to produce "job-ready" graduates that don't require workplace education, an idea that is naïve and ill-informed.

Most Australian public sector engineering organizations were abolished in the 1980s or downsized to a minimal engineering head count because they appeared to be much less productive than private sector firms. Similar changes occurred across the developed world. Few people if any realised that the public sector institutions were less productive than private firms because they were providing essential workplace education where mistakes had to be accommodated as learning experiences. Furthermore, the private firms only picked the best engineers, leaving the remainder to languish in the public sector with little hope of career advancement.

Unfortunately, after the public sector engineering organizations were largely abandoned, there has been no replacement for the post-graduation workplace education they provided.

How have firms in the private sector responded to address this critical education gap?

One response has been to lobby for skilled migration, to attract engineers *with work experience* to choose Australia as a destination. Firms preferred engineers from the UK, USA, Canada and some European countries because their experience closely matched the Australian requirements, so very little additional workplace training was needed. Migrant engineers from other English-speaking countries, particularly India, Pakistan and Bangladesh, have had a tougher time finding employment because their experience does not align so well with the local knowledge needs. However, after some years of settlement and socialization, these engineers have performed as well as other migrants and locals.

Many attempts have been made to boost local student enrolments at Australian university engineering schools. While there has been some growth, the number of graduating students has not been sufficient to meet demand. Foreign students were seen as another source of supply. Many students have come from South Asia, expecting to be hired as engineers on graduation. However, their pathway to employment has been challenging, and a high proportion end up driving taxis or Ubers. They report sending hundreds of applications with few if any replies, and perhaps one or two unsuccessful interviews. So many give up trying. Here, one of the main difficulties is that universities are unaware of most job opportunities that lie in the hidden job market: the 50-70% of jobs that are never advertised, and the large proportion of jobs filled by employee referrals, 30-50% .[23] Therefore, we see a large number of graduating foreign students applying for a small proportion of the jobs available. Compounding this is a degree of ignorance about the work rights of foreign students, and pathways to permanent residence, particularly among smaller firms, so many automatically reject approaches from graduates who do not yet have permanent residence.

Most firms, particularly small and medium size ones, are seeking experienced engineers because they feel they don't have the capacity to take on inexperienced graduates. Graduates become caught in the belief that there are no jobs that don't require experience, whereas many firms will take on an inexperienced engineer who shows initiative when they cannot find experienced job applicants.

7.1 What is meant by 'experience'?

Recent research, still to be published has listed essential engineering practice concepts and around 200 generic engineering activities in which newcomers are expected to build proficiency in their early years.[24] This, combined with knowledge of local engineering service, component, material and logistics suppliers and their capabilities, relevant standards, and relevant local construction methods largely explain what is meant by 'experience'. Implicit in

[23] Recent developments such as LinkedIn job advertising have reduced the hidden job market. The ranges quoted reflect recent US research, and similar trends are likely in Australia.

[24] To appear in my forthcoming book, Learning Engineering Practice, 2nd Edition, and available on request.

this notion of experience is the assumption that one can only develop the required knowledge, skills and attitudes (KSAs, also loosely referred to as competencies) through on-the-job experience. In other words, "experience" cannot be taught or acquired by other means. This assumption, embedded in the language, further limits recognition among employers that workplace education could meet these essential knowledge needs. As explained earlier, without a formal workplace education curriculum, novice engineers will only learn important engineering practice methods by chance.

Larger firms who recruit graduates run so-called graduate development programmes, and many of these are formally registered with Engineers Australia. Mostly they consist of work rotation schemes where engineers spend a few months in different parts of the firm until they "find their feet" and stay in a position where they are seen to be productive. From time to time, early-career engineers attend short courses, typically covering non-technical aspects such as project management, safe working, risk assessment and leadership skills. In our research, we found that engineering newcomers on these programmes felt dissatisfied because they preferred to build their technical knowledge. In their view, short courses on non-technical topics had little relevance, reducing their learning effectiveness.

In my research, I have asked senior human resources personnel in engineering firms about the process for developing their early-career engineers. Some of the responses from senior managers were surprising. In one firm, one of the largest in Australia, I was referred to a relatively new recruit responsible for graduate engineer development. This person confessed that their primary experience for the job was ten years teaching French in high schools. This person was surprised that they managed to win the job. The person said they had no idea on what graduate engineers needed to learn, but hoped to understand more very soon. Another firm, one of the largest employers of engineers world-wide, gave up trying to decide what to teach graduate engineers, and left it to the graduates themselves to decide. A major US firm with world-wide pre-eminence in the petroleum industry abolished their in-house "engineering university" that had provided formal courses for all graduate engineer trainees. The reason cited: the firm could not see a financial return on their investment.

These observations are not surprising: formal knowledge of engineering practice, a detailed understanding of what engineers are expected to be able to do, is still an emerging body of knowledge. Until recently there has been no easily accessible "curriculum" that firms could draw on for their graduate development programmes. As recently as 2005, a leading US researcher wrote in a paper that little was then known about what engineers actually do.[25]

The first instance, to my knowledge, when a research evidence-based understanding of engineering practice was instantiated formally was the current edition of Engineers Australia's Stage 2 Competency Requirements for Engineers issued in 2012. Professor Sally Male, currently at the University of Melbourne and I collaborated to introduce some research-based elements into the new revision at the time. However, the need to align that standard with the international Washington Accord restricted what could be done at the time. Non-mandatory 'indicators of competence' based on research evidence were introduced as a means to illustrate what engineers might claim in work experience statements to demonstrate they were ready to practice independently.

At that time, in 2012, Prof. Male and I recognised that there were no easily accessible texts for engineers or their employers to learn about the elements of engineering practice. To address that gap, I published my book "The Making of an Expert Engineer" in 2014, and subsequently published an introductory text "Learning Engineering Practice" in 2021. A second edition of the latter book is currently in preparation. No other research-based texts have emerged in other countries so far, as far as I can tell.

As explained earlier, even today, relatively few engineers have the good fortune to start their careers in firms with well-established systems, processes and procedures that choreograph consistently reliable collaboration among engineers and the people they need to influence. Many of these engineers miss the significance of the systems they are exposed to, seeing them as "bureaucratic impediments" rather than enablers of competence.

Even those firms with a desire to develop their engineers' capacity face significant obstacles.

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[25] (Stephen R. Barley, 2005)

a) Workplace education needs for engineering newcomers and even experienced engineers have not been clearly understood in firms,
b) Insights that have emerged from engineering practice research with the potential to lift performance standards still need to be disseminated to firms, and
c) Many firms fear that up-skilling their engineers will enable the engineers to seek higher paid work for other firms.
d) Few if any engineering firms allocate time and budgets for workplace education of their engineers. Instead, the time is billed to ongoing projects and often relies on supervisors working extra hours without additional pay.

Even if these obstacles can be overcome, there are knowledge gaps that result in a mistaken focus on building the competencies or proficiencies of individual engineers. One only has to read a small cross section of the literature on engineering competencies to realise that the influence of the firm and its systems, processes and procedures is invisible to most writers. Therefore, workplace education of engineers is only part of the solution. Another part of the solution lies in encouraging firms, particularly small and medium sized firms, to develop the systems, processes and procedures on which successful engineering collaboration depends.

We need much more awareness among engineers and their employers of the critical intersection and interactions between technical requirements and constraints, commercial imperatives, investors' expectations, the motivations of people who work in engineering enterprises, and formal collaboration methods.

Some people might argue that these issues are adequately addressed by engineering management degrees, or MBA courses. However, I argue that it is engineers, their supervisors and business owners working on front lines of engineering projects, large and small, that need these insights, not just managers. Only then will we have a decent chance of reducing the extraordinary losses we are witnessing today in engineering projects and enterprises.

7.2 Research is robust but more is needed

The research behind this submission is substantial, and is based on hundreds of qualitative interviews with engineers and their managers from novice to CEO level in several countries. Supporting evidence has come from engineering practice research in other countries.

However, more research is needed.

We can be reasonably confident in identifying knowledge gaps among the cohorts of engineers currently practicing in Australia.

However, we cannot yet be confident that closing these knowledge gaps through various forms of post-graduation workplace education will contribute to substantial reductions in the avoidable costs identified earlier. More research is needed, and that requirement is addressed in the policy proposal that follows.

8 A national agency for registering engineering firms

The argument I have developed so far is that reducing avoidable losses in engineering projects and established enterprises will require considerable new learning on the part of engineers and their employers. Current workplace learning is inadequate in so many respects and firms need more incentives to build their capacity, as well as implement appropriate systems and processes to create the environment that engineers need to enact the kinds of collaboration needed to move beyond current unsatisfactory performance standards.

Relying on universities to address this education need is unrealistic, given the lack of recent engineering practice (or any at all) among engineering faculty.

Unfortunately, even the limited evidence provided above demonstrates that the current state-based engineering registration systems cannot ensure that engineers practice competently, with professional standards of practice accepted in similar countries such as Europe, USA and Canada. Furthermore, the current registration system cannot be expected to address the gaps in knowledge that we need to reduce large and avoidable financial losses identified above.

Here I argue that a national engineering registration agency for engineering firms (NERA) is a more appropriate response.

Initially registration would be voluntary for all except firms involved in work posing large safety or environmental hazards such as apartment buildings over a certain height, major energy and chemical plants, nuclear installations, tunnelling, large underground or open cut mines, facilities with bio-hazards, etc. One might also include firms undertaking work with significant social implications, particularly in the information technology space.[26] As the agency demonstrates its benefits, registration requirements might be widened beyond these firms.

Registration of engineering firms at a national level should achieve better outcomes for businesses and the Australian society than the separate, cumbersome state-based schemes that focus on individual engineers with little mutual recognition.

As part of the registration process, firms would be audited to establish capacity and performance ratings with built-in workplace education incentives for firms, a measure that could significantly improve the performance of engineers and the firms that employ them.

Certification of individual engineers from professional organizations could continue, but there would be no need for the current state-based registration schemes.

Such a scheme would eliminate workforce mobility barriers imposed by the current state-based registration schemes. With appropriate design, a national registration scheme for engineering firms could also significantly reduce barriers faced by migrant engineers entering the Australian workforce.

The stated purpose of an engineers' registration scheme (adapted from Engineers Australia) is "it ensures engineers meet benchmarked education, training, professional conduct and competency standards. These standards help consumers feel confident in the abilities of the

[26] We have seen how failure by software engineers to take the social implications of their work into account has led to legislation to ban social media for children under 16 in Australia.

engineers they engage. They also ensure there's a legislative framework in place to protect against sub-standard practice."

I advocate national registration for engineering firms, because the firm, its culture, systems and processes, are known to be the dominant factor that shapes the performance of all its employees, including individual engineers.[27] Decades of experience with corporate regulation in many countries have demonstrated that regulating firms is necessary, rather than regulating individuals alone. Corporate regulation in Australia, over time, has moved from the states to the federal government because so many firms, large and small, operate nationally. Many firms operate internationally as well, thanks in part to the reputation that stems from Australia's system of corporate regulation. While the Australian Securities and Investment Commission (ASIC) provides over-arching corporate registration and regulation, a specialist regulator, the Australian Prudential Regulatory Authority regulates banking and finance institutions. NERA would, in the same way, complement ASIC.

As a federal agency largely funded by industry stakeholders, NERA could ensure that competent and appropriately experienced staff operate the scheme to a much greater extent than an individual state's public servants. Firms would be reviewed and awarded ratings indicating their financial strength, discipline expertise, engineering capability development and training, strength of their systems, processes and procedures, and quality management.

NERA would have three principal objectives:

1) Consumers, companies and governments who hire the services of engineers would feel confident that firms meet benchmarked performance standards matching or exceeding those in similar countries.
2) Power to implement sanctions against a firm is an effective incentive for firms to maintain performance standards, and more powerful than sanctions against individuals.

[27] (Bea, 2000; Brady, 2024; Busby & Bennett, 2007; Chatman & O'Reilly, 2016; Martins & Coetzee, 2007; Tellis, Prabhu, & Chandy, 2009; Turney, 2014)

3) NERA would audit important aspects of registered engineering firms, evaluating their capabilities and performance, and publishing ratings for each firm. Auditors could take into account factors such as:
    a. Financial capacity – influencing the size of projects they can service;
    b. Staff qualifications and awards – relative to the headcount, the accumulated length of experience of engineers, years of first-hand experience of site engineering, and the proportion who have achieved chartered or equivalent status granted by a relevant professional society;
    c. Areas of practice with sufficient expertise to take on projects in a given size range;

Performance ratings might include the following:

   d. Project portfolio in the last five years, awards demonstrating exceptional performance;
   e. Confidential feedback from clients;
   f. Demonstrate capacity of the firm's systems and procedures to build and maintain their engineers' proficiency, and maintain service quality standards.
   g. Demonstrate capacity to maintain high standards of ethical behaviour.

NERA, with an appropriate mandate, would enable the accumulation of an evidence-based body of knowledge on engineering practices in Australia and other countries that result in superior economic and social value generation, and also provide accessible de-identified accounts of engineering practice failures to enable all firms to learn from past experiences. The agency would be responsible for helping firms ensure that they can deliver effective workplace education for their engineers.

As a federal agency, NERA would be governed by a board comprising federal government and industry stakeholder representatives. It would be funded partly by the federal government and partly from audit fees paid by registered firms, with the fees dependent on a firm's financial size.

Evidence presented earlier has demonstrated the need to significantly improve delivery performance on engineering projects across all sectors of the economy. Other evidence demonstrates potential for improvements in operation and maintenance standards across all industries.

NERA would commission appropriate research to build a body of knowledge on engineering practice from which all firms can learn how to improve their own performances. This research would provide help to provide the essential feedback of learnings from engineering project and enterprise failures that is missing today.

Firms seeking registration would need to institute formal practices and procedures to ensure that engineers allocate appropriate priority for checking and due-diligence on work with significant commercial, environmental, or safety risks.

Audits of engineering firms instead of registering individual engineers would place a much stronger responsibility on firms to develop the competencies of their engineers.

Strengthening post-graduation education for engineers could help overcome several current practice weaknesses, including the following.

- Strengthening the understanding among engineers on their roles in national productivity improvement. Today, most engineers do not understand notions of productivity except in a very localized sense, seeing it in terms of the throughput of processes for which they are personally responsible.
- Strengthening engineers' understanding on how to generate commercial value, described in the section Value generation in ordinary, everyday, routine engineering, should gradually help break down the separation of business understanding from technical engineering knowledge described in the section Separation between technical engineering and business thinking.
- Strengthening understanding among engineers about the influences of the organisations employing engineers, further explained in the section Organisation is the main influence on performance, could help increase the growth of many firms.

Most engineers do not understand this, seeing these systems as impediments and inconveniences rather than enablers. While large firms depend on organisational systems and procedures, many small firms have poorly developed systems. This might explain why productivity improvement is much slower in small firms.

- Helping engineers understand the value generated by collaboration activities such as systematic checking and review might help attenuate an instinctive tendency to de-prioritize, relegate or defer collaboration activities that engineers see as "not real engineering work". Collaboration weaknesses explain most engineering failures and are often among the root causes of today's appalling project delivery performances. Once engineers see the entirety of their work as "real engineering", they may be more inclined to seek improvements.

  At a fundamental level, for example, many young engineers instinctively prioritise text communication over face to face interactions, without awareness that this can quickly undermine trust on which successful collaboration depends.

8.1 What would count as unsatisfactory practice?

This is a crucially important question because no regulation of performance standards can be effective without such a definition. With so many fields of engineering (about 350 at the last count), performance standards cannot be uniformly applied. Performance standards for computer software development, for example, cannot be the same as for bridges. One cannot issue a design update to stop a bridge beam from cracking after the bridge has been built, but a gradual process for eliminating coding mistakes with regular updates has become an accepted practice in software development.

Here I propose to fall back on the sequence of activities intrinsic to almost any engineering project. Once the requirements have been identified and appropriate designs chosen, engineers build a business case for investment, justifying the expenses with long term income-earning capacity. The final investment decision, therefore, reflects assurance by engineers that the ultimate performance of an artifact aligns sufficiently well with investors' expectations.

From this, we can deduce that unsatisfactory performances by a registered engineering firm will either result in assurances that cannot be met or, the ultimate performance of an artifact does not reasonably align with investor expectations. In other words, unsatisfactory performance can be framed as circumstances in which the artifacts resulting from engineering work by a registered engineering firm fail to meet reasonable performance expectations.

There are two possible approaches to assess whether engineering work has failed to meet reasonable performance expectations. The first and more costly is to arrange for engineering expert witnesses to argue different viewpoints in a court presided over by one or more judges based on their experience on technical expertise. Each expert would be briefed by counsel representing parties to the matter in question. At a minimum, one party would be NERA itself, and the other the engineering firm alleged to have failed to meet reasonable performance expectations. The client or project owner might also be a party to the matter, with their counsel briefing their own expert.

A less costly approach would be based on a commercial arbitration model. This might see the parties agreeing to have the matter heard by a tribunal with an independent chair or arbitrator. The arbitrator would not be involved in the industry represented by the parties, would have legal training, would likely have experience of engineering disputes, and would also have experience as a tribunal chair or arbitrator. The parties would need to agree to accept the chair or arbitrator's decision, and to forgo their right of appeal unless denied natural justice by the process. Each party would appoint their own engineering expert to present their side of the matter to the tribunal.

There might be some restrictions on who could initiate these proceedings. NERA could initiate proceedings on receiving reasonable evidence that a registered engineering firm may have failed to meet reasonable performance expectations. More likely, a complaint would come from a client organisation or a project investor. They might first approach NERA for a preliminary assessment. Unless NERA provides a sufficiently convincing argument that the complaint is unjustifiable, the complainant(s) would then lodge a formal case with NERA to initiate a tribunal process.

There are many possible refinements: the aim here is to propose at least one model to decide whether a registered firm has failed to meet reasonable performance expectations.

There is one more important issue here. A tribunal decision on whether a registered engineering firm had or had not met reasonable performance expectations would not prevent an aggrieved party from seeking redress or compensation through existing legal pathways, either commercial arbitration or through the courts. Of course, such a decision might significantly influence those separate proceedings.

8.2 What sanctions might be appropriate?

The threat of sanctions is likely to be essential to motivate compliance with expected performance standards. Indeed, a national registration system that does not sanction registered firms that fail to meet reasonable performance expectations would not be regarded as an effective regulator.

Deregistering an engineering firm would be the ultimate penalty. This would prevent a firm from taking on work with major safety, environmental or social implications. However, particularly in the case of larger firms, performance deficiencies are more likely to arise in a particular section a firm. Deregistering a large firm might also reduce competition between firms.

Adjusting published performance ratings provide a more gradual series of options for sanctioning firms. Firms might be classified by a star-rating, from five stars applicable for the top performing firms, to one star for start-ups with minimal performance records.

Then, instead of deregistration, a firm might have their performance ratings in one or more categories reduced if they fail to meet appropriate practice standards, with a mandatory waiting period before the firm could apply to have their ratings reassessed and restored.

In this way, published performance ratings would not only provide incentives for firms to develop their engineers' capabilities, but also provide a graded set of sanctions that would be less catastrophic for engineering firms than deregistration.

8.3 Who would pay?

Apart from some core government funding, engineering firms would cover most of the operating costs for NERA, in proportion to their engineering headcount and turnover. The agency would collect sufficient funds for applied research to identify workplace education needs and develop pedagogy and learning resources.

8.4 Implementation

NERA might gradually extend its coverage, starting with major engineering firms. As the staff gain experience, the audit process would be gradually refined to provide a more representative method to classify engineering firms, from the smallest to the largest. Audit ratings might normally last for five years, with five-yearly audits after initial registration. Any major restructure of a firm such as a takeover by another firm would normally trigger a new audit some time after changes resulting from the takeover had come into affect.

As explained in the introduction, if NERA works as expected, there would be substantial benefits for firms to register and gain published performance ratings. Extending mandatory registration requirements might not be necessary because of the benefits for business development from being able to promote a firm's ratings.

8.5 How would this help project owners exposed to costs of failures?

Project owners are not normally classified as "engineering" organisations, yet they rely on engineers both within their own firms and as service suppliers. While they would not register as engineering firms, they could register in a special category "engineering employers." Their own engineers would need workplace education just as much as engineers working for registered engineering firms.

The "engineering employer" category would be available to any firm engaging engineers, directly or indirectly. These firms could request an audit for directly employed engineering sections within their firms on a fee for service basis. Access to best practice information for project owners would also be on a fee for service basis.

Project owners have an essential role in reducing avoidable costs by sharing their experiences and best practices. As explained in the discussion above, the current culture among project owners is averse to sharing knowledge of failures, perhaps to avoid adverse shareholder reactions. However, as a nation, or even as an international community of engineers, one of the best ways to avoid future failures is to learn from past failures.

The research arm of NERA could provide a confidential means to share knowledge of failures, while preserving the confidentiality of information regarded as sensitive by project owner firms.

Avoiding future project failures will rely on project owners being informed: they have an interest in adopting better practices. By contributing to applied research, they will be more likely to adopt the findings.

Naturally, it would probably not be appropriate for NERA to initiate or encourage complaints against firms in the "engineering employer" category. However, engineering firms experiencing unreasonable treatment from a firm employing their services might desire some process to, for example, trigger a ratings review. I expect engineering firms might want a say in deciding what kind of process might be appropriate. For example, registered engineering firms might reasonably demand that an owner organisation commissioning engineering work with significant safety, environmental or social implications to register as an engineering employer and have sufficient ratings to act as an informed buyer of engineering services.

8.6 Foreign engineering firms

Foreign engineering firms operating in Australia would have to be registered with NERA if they are conducting work with major safety hazards in the same way as local firms. Registration would otherwise be optional, as for Australian firms. In that way, NERA would not pose a significant trade barrier for foreign firms.

8.7 Government agencies

Government agencies commissioning engineering work are particularly vulnerable to project execution failures, as explained earlier in this submission. Changes in political priorities can result in scope changes that can severely affect project completion and benefits. For example, a major recent government construction project in Perth city was disrupted after the project was approved by a political demand to incorporate underground car parking. The result was a very large cost increase and delays in completing the project.

Government agencies have resisted approaches from firms such as IPA Global to engage in evaluation of projects before final investment decisions and subsequently after completion. Private sector project owners tend to decline to make their project failure experiences available for engineers to learn from. Both sectors, therefore, are largely preventing the possibility of learning from their experiences to reduce the risks of future failures.

Therefore, it is reasonable that government agencies should engage in thorough project evaluation practices before projects are approved and after projects have been completed, and make their experiences available to improve workplace education by engineers.

Government agencies could also register with NERA as engineering employers to help improve their ability to commission engineering projects effectively.

9 Counter Arguments

Here I briefly address several possible arguments against the proposal in this submission.

9.1 Project failure costs

I concede that my methods to estimate project failure costs are simple and should be subjected to rigorous examination. However, even if I have significantly over-estimated them, the costs are still likely to be very large. A more detailed examination is worthwhile, and deserving of government attention.

9.2 Project failure costs might not be avoidable

We might have to accept that large engineering projects, even ones that involve little or no innovation beyond scaling up well-known solutions, might be inherently risky. However, it is likely that providing engineers with appropriate education can make a difference to outcomes. After all, it is easy to accept that failing to teach engineers about the limitations of bridge-building materials would result in more bridge failures. Therefore, by the same argument, improving education on the causes of engineering project and maintenance failures is likely to reduce the costs of such failures. As I have suggested, given the very large costs, even a 10% improvement would yield substantial annual benefits. The cost of improving workplace education for engineers is likely to be far less than the benefits and worth a serious attempt. Naturally, as one increases the targets for avoiding unnecessary project failure costs, the cost of preventative action might rise.

9.3 Registration is unnecessary because the market can overcome performance issues

Markets can be a good way to help reduce costs provided buyers are well-informed. Unfortunately, there is strong evidence that, in the case of engineering services, many buyers are ill-informed.

Available evidence indicates that engineering project delivery performances and potentially avoidable engineering costs are worsening over time. In this document, I have explained that most project owners are not sharing their experiences of project failures, an essential process if future failures are to be avoided.

Our research has also shown how many buyers of engineering services simply choose a provider with the lowest hourly fees which may be a contra-indication of the value they can provide. A large variation in hourly fees, with the highest nearly four times the lowest in some fields we gathered data for, reveals that many buyers are prepared to purchase engineering services from firms with less than ideal performance and capacity to provide value. In other words, many buyers of engineering services are likely to be ill-informed. Government agencies outsourcing engineering work may be some of the least informed buyers: we have ample evidence of engineering performance problems that arise from choosing a lowest cost provider.

Private firms may also be ill-informed. We have some evidence of a trend by private project owners to choose a single provider for a major project to reduce their due diligence workload. Especially when a single provider engages many subcontractors, it can be difficult or impossible for the project owner to gain critical feedback from project sites to understand what is really happening with their projects.

9.4 Is it right to dismiss individual registration?

The chartered engineer qualification, the national engineering register, and the EngExec qualification (all Engineers Australia initiatives) are forms of individual registration which have been operating for many years. RPE (Queensland) is a century old. The other states, led by New South Wales have recently started their own registration.

Engineering project losses have continued under these schemes, and there is no evidence of any improvement as a result of registration. As I have argued, none of these schemes requires engineers to obtain independent reviews of safety-critical aspects of their work. Peer review within firms, as demonstrated by our research, is relatively ineffective.

Recent scholarly research[28] has questioned the societal benefits of such schemes. So it is hard to argue in favour of these schemes.

9.5 Organisational influence may be overrated

Yes, it is possible that exceptional engineers can succeed within poorly organised firms, and yes, it is possible that well-organised firms can be undermined by incompetent engineers. However, the available research evidence on the influences of organisational systems in firms and culture is hard to argue against, notwithstanding that most of the research has not focused specifically on engineers.[29] While the degree of a firm's influence in a particular situation might be debateable, the significance of the firm's influence is incontestable.

9.6 Criticism of contemporary engineering education?

This submission might be interpreted as a criticism of contemporary engineering education which increasingly emphasises project and team-based learning. It is not intended to be a criticism, rather a recognition that university engineering education can only provide part of

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[28] E.g. (Law & Sukkoo, 2005; Robinson, 2018)

[29] E.g. (Chatman & O'Reilly, 2016; Igo & Skitmore, 2006; Martins & Coetzee, 2007; Trompenaars & Hanpden-Turner, 2021)

the education needed to practice engineering. University engineering schools have never claimed to be able to provide all the learning needed which is why lifelong learning is emphasised as a highly desirable graduate attribute. What is argued in this proposal is the need to ensure a more comprehensive coverage in post-graduation workplace education for engineers, and the lack of any current capacity in the university system to provide that.

9.7 Implementation difficulties

It might be argued that the cost of implementing registration and ratings audits, combined with the cost of providing more comprehensive workplace education for engineers and other staff might be more than the benefits. Given the magnitude of the costs currently being sustained by the Australian community, that might be a difficult argument to sustain. The purpose of this submission is to propose a closer look at national registration for engineering firms. Further debate and investigation, and a thorough examination of this proposal by interested stakeholders might not, in the end, provide sufficiently supportive evidence. However, the financial magnitude of the issues raised makes such a debate worthwhile.

Another implementation difficulty that has affected the state-based schemes is recognising different areas, branches, disciplines or fields of engineering. All four terms are used from time to time. Clearly, recognising all 350 or more known fields of engineering would be unwieldy. Therefore, it might be best to let registered firms decide on which fields of engineering they want to advance as areas of competence. The dispute resolution process outlined above should provide a reasonable way to deal with any issues arising from that.

At this time, I have not attempted to consult with major engineering firms. The purpose of this submission is to draw attention to the potential productivity benefits from improving the post-graduation workplace education for engineers. The proposal for a registration agency is merely a policy suggestion which could provide firms with appropriate incentives to invest in improving the education of their engineers.

I have consulted with Engineers Australia and many individual engineers over the last few weeks. I have incorporated many improvements from suggestions arising from these consultations.

9.8 Regulatory capture risk

Is it possible that the ratings process might be "captured" by large firms or political interests to their advantage at the relative cost of smaller firms, and serve as a trade barrier against foreign firms? I do not think this has happened in other significant industries such as the banking sector where APRA provides regulation. I think that Australia has sufficient experience with regulation to avoid these undesirable side-effects.

9.9 Questionable causation?

Is it possible that we do not understand project and engineering maintenance failures sufficiently to provide workplace education that would be effective?

Yes. However, the magnitude of the financial impact suggests that significant research, perhaps costing $1 million, might be a good way to find out. I have suggested building research capacity as part of this proposal to maximise the likelihood that we can avoid significant costs with appropriate education. After all, we know that we have reduced other kinds of engineering failures with improved education. Why should we deny the possibility of further engineering performance improvements?

9.10 Engineering firms already have to be registered in WA

Surely, the Western Australian registration requirement could be rolled out nationally to achieve the same objectives.

The WA scheme for engineering firms only covers the building industry and provides no incentives to improve post-graduation workplace education for engineers, the core motivation for a national agency such as NERA. Like other registration schemes, the WA scheme does not cover most engineering firms performing work with major safety, environmental or social implications.

9.11 Registration for firms might inhibit job mobility for younger engineers

Is it possible that registered firms might be reluctant to hire engineers from non-registered firms because they have less relevant experience or have not met the continuing professional development (CPD) requirements for chartered engineer status?

While this cannot be ruled out, it is unlikely. A good record of CPD is a desirable, most potential employers will take a much closer look at a job applicant's record of engineering achievements. Currently, in Engineers Australia, CPD requirements can be met with 50 hours of participation in activities such as seminars, conferences, private reading, etc. over three years. There is no requirement for learning assessment: that's equivalent to claiming a degree for lecture attendance without having to pass exams.

A registered firm will normally evaluate job applicants for their capacity to deliver value for the firm and potential to further develop their capacity with appropriate further education. The audit ratings will reward firms for their processes to further develop the capabilities of their engineers.

9.12 Is there a better way to lift engineering practice standards?

Possibly. However, the status quo is unacceptable. I am always open to receiving better suggestions.

9.13 Surely, AI will solve these problems

Artificial intelligence is changing engineering work by providing faster access to more appropriate information. So far, however, there is little evidence that AI will solve the organisational and collaboration issues that lie at the heart of the avoidable costs described at the start of this submission. As explained earlier, the requirement for effective peer review could be even more challenging with greater reliance on AI in engineering. As research has shown, different approaches are needed overcome the apparent weaknesses in peer review for design checking to be effective.

10 Supplement

This supplement provides additional background on relevant engineering practice research findings.

10.1 Design checking weaknesses

The first discovery concerned design checking.

An engineering design consists of hundreds if not thousands of documents: text, images, maps, diagrams, drawings and various computer-based representations of the design. The documents emerge from a collaborative process involving project owners, contractors, specialist designers, project engineers, process engineers, suppliers of components, and manufacturers. These documents are supposed to be rigorously checked by senior engineers in the same firm, and sometimes engineers in external firms hired to perform an independent design review.

On large projects, the engineering project team will hire an independent audit team to check that all the review copies of every document have been marked up and signed by engineers assigned to check them. The audit team will also ensure that there is an audit trail for every design change providing the implications of the change, and an acknowledgement by engineers in different affected departments that they have been consulted and have approved the changes.

We first noticed anomalies when a final year engineering student disclosed that his summer vacation work was checking design calculations and documents "because the senior engineers were too busy and didn't have enough time to meet the checking deadlines." It seemed odd that this work had been assigned to the least experienced person in the firm, without any detailed supervision. This student subsequently wrote a thesis revealing that almost all engineers in the firm performed only superficial checking at best, and were known to sign documents to confirm they had been checked when, in fact, no checking had been performed. The senior managers in the firm, at the same time, were worried that their projects always seemed to be running behind schedule because of design mistakes that were only discovered when components did not fit where they were supposed to go, or were incompatible with equipment that had already been installed on site. These were mistakes that should have been detected at the design stage before starting equipment manufacturing and procurement. When confronted with the results of our research, the senior managers declined to engage: they were clearly concerned about reputational damage.

Further research revealed that this pattern of behaviour was widespread across many industries. On one occasion, we were invited to inspect a dozen thick printed documents by a project team leader who proudly told us that a recent audit of their review processes had revealed zero non-conformancies among millions of document checks. In research interviews, engineers confessed that they either delegated checking to junior staff and, on occasions, even in some critical cases, performed no checking at all. A quick inspection of the documents taking less than an hour revealed many simple errors such as missing pages, diagrams with print so small as to be unreadable, references to non-existent documents, and missing statements of assumptions for design calculations.

Other researchers have reported similar issues.[30]

These observations contribute a significant finding: design checking weakness could explain delays and cost increases in engineering projects.

One might ask how engineering can be so apparently reliable most of the time.

It is reassuring to know that engineers have evolved many 'protective' methods to deliver reliable results despite human behaviour weaknesses. Engineering standards provide many quick and easy 'recipes' that help engineers reach solutions with less chance of making mistakes. The widespread practice of copying earlier designs with minimal modification, even though the cost might be higher as a result, reduces the risk of failure. Third party review provides a more effective way to check designs: psychologically, engineers may be more likely to detect errors in work by people they do not know, compared with checking work by their

[30] See for example, the story of a platform audit (Bea, 2000). The Therac-25 failures exposed weaknesses in checking software and developing rigorously checked software statements of requirements (Leveson, 2017).

colleagues. Finally, by building in large safety factors and redundancy, component failures can occur without catastrophic consequences.

10.2 Notions of value generation

Gradually we realised that there might be a systematic sociological issue that could explain this widespread disinclination by engineers to engage in checking work. Value expectancy theory[31] pointed to understandings on how value is generated as an explanation. Clues emerged from comments by some design engineers explaining that, in their opinion, design checks delay completion, add cost, and hold up "productive engineering work". The value created by avoiding the much higher cost of fixing mistakes later in the project was not apparent to these engineers.

When we conducted new research interviews to understand how engineers perceived their role in value generation, we discovered that most engineers have only a weak understanding on how their work creates economic value. Differences in understandings of common English language words contribute to this difficulty. For engineers, value implies a number with a quantifiable degree of uncertainty, a meaning quite different from notions of value in a discussion on economic value creation.

10.3 Separation between technical engineering and business thinking

Another contributing factor lies in the discipline "walls" that separate business and engineering. Engineering faculties in universities, from the 1980s onwards, outsourced all teaching on finance to business faculties. However, business schools have eschewed understanding the relationships between technical issues and financial outcomes, except research, development and innovation. The extensive discussions on, and promotion of entrepreneurial technology start-ups in recent decades reflects this interest. Innovation is seen in business schools as a key driver of economic growth and prosperity.

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[31] (Eccles, 2005), cited in (Trevelyan, 2012)

The word cloud that follows is one way to illustrate the separation in thinking between engineering and business. It resulted from asking a group of 30 New Zealand engineers what engineering is, in a study on the economic impact of engineering. There is only a marginal reference to the word 'value', no mention of business, nor the economy, nor productivity.[32]

10.4 Value generation in ordinary, everyday, routine engineering

It is important to realise here that most engineers are not involved in innovation. Data reveal around 3% of engineers participate directly in R&D and related activity. Most clients demand well-tested, industry-standard solutions because they are well aware that innovation introduces added uncertainties and commercial risks.[33] We discovered a theory gap in business and finance: there seemed to be no understanding on how ordinary, everyday engineering like sewerage plants contribute economic value. However, it was clear that many

[32] (Gould, 2020)

[33] (Trevelyan & Williams, 2018)

of the large engineering projects that were failing to meet investors' expectations were replicating well-known engineering solutions, yet at the same time were definitely destroying economic value.

Subsequently, we identified many ways in which ordinary, everyday, non-innovative engineering generate value.

1. Value is created when investors (and banks) commit finance.
2. Value is delivered when the engineers deliver working products, process plants, infrastructure, or systems that meet or exceed investor expectations.
3. Value is protected from inadvertent loss by maintenance and sustainment activities, and by maintaining a social licence to operate.

10.5 Weak understanding on generating value and productivity

Research evidence demonstrates that most engineers have only a weak understanding at best on how their work contributes economic value and productivity improvements. They know little if anything about the major project failures littering the engineering landscape of Australia and other countries. Their university education provides weak if any foundation to provide economic solutions, build their people skills and understanding on how business and technical engineering are linked. In addition, we now know more how smart phones and social media have undermined the ability of young people to build social relationship skills.

Engineers learn next to nothing about finance, economics and people in their university engineering courses. Nor do they learn how to create economic solutions, minimizing material cost and energy needs. Discipline silos prevent students from learning the intimate links between people, business, finance and technical engineering. The formal infrastructures of higher education contribute to a competitive, anti-collaborative culture, particularly the emphasis on written assessments to gain individual grades. It takes years for universities even to decide that curriculum changes are needed, and another decade before graduates might start influencing workplace practices.

10.6 Organisation is the main influence on performance

A further research finding, still to be fully written up and published, concerns the influence of organisational and social culture. The price that clients pay for work by engineering firms, in terms of hourly rates or fees, clearly reflects the value that clients perceive is being provided by the firms. We found a large variation in these rates in similar markets, both within Australia, and also between Australia and developing countries such as India and Pakistan. The theory of marginal productivity gains also tells us that, notwithstanding some market rigidities, engineers' salaries also reflect value generation capacity.

Most larger engineering organisations have managed to grow from small firms because they have developed systems and processes to improve value generation for their clients. For example, a large Australian-based firm employing tens of thousands of engineers world-wide managed to do this by delegating decision-making using an instrument that evaluated the commercial risk, and permitted less experienced engineers and managers to make low-risk decisions without reference to senior management. This freed up the time of senior managers to spend much more time on decisions involving large commercial risks.

These observations help to show that the performance of individual engineers is substantially influenced by the systems, procedures and culture of the organisations that employ them. Many engineers regard these systems and procedures as unnecessary bureaucratic hurdles that impede productive engineering work. They cannot see how these same systems and procedures actually support their work, largely by choreographic collaboration, helping to ensure that information reaches people who need it to make informed decisions. Many engineers yearn for the freedom to work in small, innovative firms where informality allows them greater autonomy. Yet, the absence of systems and procedures can often explain why these small firms remain small.

A supermarket is a useful analogy, described by Bruno Latour[34] as an instant enabler of competence. The logistical systems, checkouts, barcodes, product packaging, aisles, shelves,

[34] (Latour, 2005)

product displays and even trolleys all combine to enable a bunch of relatively unskilled teenagers to run a profitable, multi-million dollar business in a highly competitive market with low margins. In the same way, the systems, procedures and processes created within large engineering firms enable competence by their engineers, even relatively inexperienced early-career engineers, and clients pay premium hourly rates to obtain their services.

10.7 Distinguishing professional engineers from other engineering occupations

Before proceeding further, it is useful to understand how professional engineers can be distinguished from technologists, drafters, computer programmers, tradespeople and technicians. (People with a background as technologists and technicians can also be known as engineering associates in Australia).

The international Washington, Sydney and Dublin accords frame three engineering occupations, professional engineers, engineering technologists and engineering technicians respectively.[35] The International Engineering Alliance (IEA) is the organisation that "owns" these accords and periodically updates them after extensive international consultation. In this document, I refer to professional engineers as 'engineers' for simplicity. However, the term 'engineer' is often used by people to describe technicians or technologists.

The aim of the accords is that engineering qualifications would be mutually recognised in a wide range of countries to promote the mobility of people with engineering knowledge, expertise and skills. About 30 countries have ratified the Washington Accord and around 10 have signed on to the Sydney and Dublin accords. So far, these accords have improved the mobility of engineers and mutual qualification recognition for membership of professional societies. However migrant engineers, technologists and technicians still encounter acute difficulties in gaining recognition for their qualifications and employment experience in Australia and other countries.

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35 (International Engineering Alliance, 2021)

It can be difficult to distinguish the occupational classification for a particular person because of the ways that the different occupational groups are distinguished in the accords, mainly by education attainment and cognitive skill levels. A significant difficulty reinforced by the accords is the implied occupational hierarchy, placing engineers on top, technologists in the middle under the direction of engineers, and technicians at the bottom, taking directions from both engineers and technologists.

A perennial issue among engineers is the tendency by many technologists and technicians to identify themselves as engineers.

Here I will present a simple way to distinguish each of these groups from the others based on occupational sociology research in the last few decades.

All three broad engineering occupations rely on specialised knowledge that other people usually do not have, partly as a result of their formal higher education, and partly acquired through workplace training and experience.

Research on engineering practice, observations of engineers at work and ethnographic interviews with them,[36] has led to the following broad definition of engineers:

Engineers are people with specialized technical knowledge who collaborate with other people to conceive, deliver, operate and sustain artificial objects, systems and processes. These artefacts enable people to be more productive, to do more with less effort, time, materials, energy, uncertainty, health risk, and environmental disturbances.

This definition is more a description of the collective endeavours of engineers. It helps to distinguish engineers from other people such as scientists, nurses, shopkeepers, and sales assistants. This definition could also be interpreted to include architects and product designers.

[36] Definition proposed by the author based on research, partly by the author and his students, and by analysis of published accounts of research on engineers and technicians between 1980 and 2024.

At this point, the types of specialized technical knowledge used by engineers can help us distinguish engineers, engineering technologists, and engineering technicians from, say, architects and product designers. For example, a person who has completed a recognised higher education programme of study in engineering has acquired specialized engineering knowledge. However, we need to acknowledge that some people can acquire engineering knowledge through self-guided study or work experience. We can distinguish their knowledge with reference to formal engineering study programmes, and if the knowledge gained from informal learning is largely equivalent, then we can say that these people have also acquired specialised engineering knowledge. Therefore, we can say that people who have acquired engineering knowledge can be said to be engineers, embracing not only professional engineers, but also engineering technologists and engineering technicians.

Architects and product designers can also be distinguished from engineers by their primary intellectual focus on the subjective visible external appearance and apparent function of artefacts such as buildings or physical products. Engineers, on the other hand, are primarily concerned with typically invisible aspects of artefacts necessary to provide safety, durability, constructability, cost, and environmental impact.

Beyond the ability to distinguish engineering from other occupations, we also need to distinguish between the different occupational groups within engineering. An individual engineer is likely to contribute only a part of the collective engineering effort described in the definition above. A technician, for example, may be testing components purchased from a supplier to verify their suitability, and might not play a direct part in delivering or operating an artificial object or system. An individual engineer may analyse the performance of part of an artificial object or system and deliver a report that helps to justify an investment decision, but does not directly contribute to the operation or sustainment of an artefact or system. A technologist such as a programmer might generate a program that controls the operation of a machine tool to generate a particular component, but does not contribute to, for example, sustainment of the end product.

In the 1980s, occupational sociologists evolved ways to distinguish different occupations by

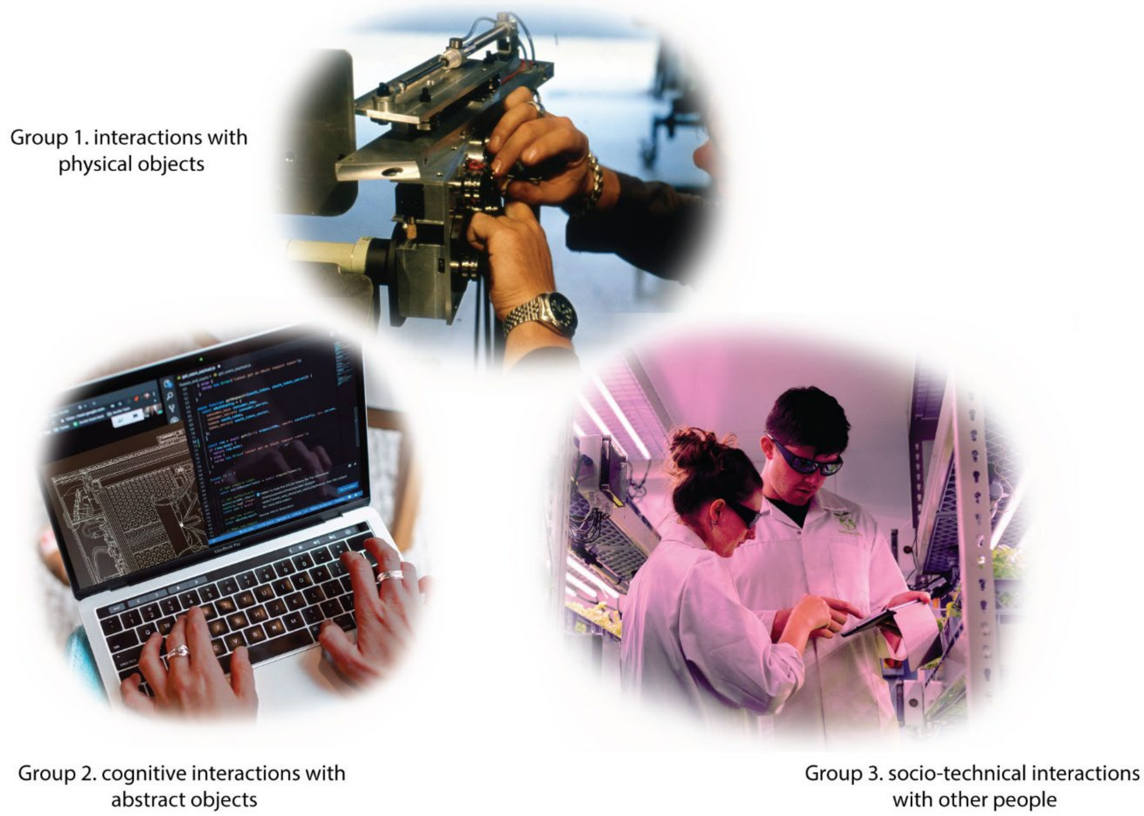

Figure 1. Engineering occupational activities identified by occupational sociologists. Most technicians' work corresponds to group 1 activity, most technologists work corresponds with group 2. Engineering work predominantly consists of group 3 social interactions.

analysing observations of workplace activities. They proposed three activity groups illustrated in figure 2.[37]

i) Work requiring motor skills, hands-on work in which people manipulate physical objects and tools;
ii) Work requiring cognitive or thinking skills, interactions with abstract objects and ideas;

[37] (Howell & Wolff, 1991; Zuboff, 1988)

iii) Work requiring social skills, interactions with other people, either face to face, or at a distance in space or time.

Observations of technicians reveal extensive requirements for group 1 activity requiring manual dexterity and often complex sensorimotor skills that can be hard to identify, emulate and replicate.[38] It takes years of supervised and independent practice to develop these skills which also include the ability to assess whether the quality of work is appropriate for the particular application, and to sense, diagnose, compensate for, and correct defects in tools and materials. Technicians are also expected to develop an extensive understanding of relevant industry standards and practices, and to understand when and how these standards and practices should be applied. They will also develop knowledge of suitable suppliers for tools and materials, and will be able to assess the quality and appropriateness of tools and materials for a particular task. They will also be able to read and interpret engineering drawings or models that define the requirements for a particular set of tasks, and choose appropriate tools and materials to complete the task with an appropriate quality.

Engineers, technologists, associates and technicians all interact socially with other people because collaboration is an intrinsic feature of engineering work, particularly in supervisory roles. For example, a production supervisor, relying on extensive experience as a technician, also may engage in cognitive interactions with computer systems and also performs extensive social interactions as well.

Engineers carry responsibilities for the suitability, function, efficacy, safety, cost and environmental impacts of artefacts and systems, and the methods to construct, install, assemble, test and operate artefacts and systems. They mainly achieve these objectives this by influencing the work of other people: technologists, technicians, tradespeople, contractors, financiers, suppliers, regulators and many others. While some might see these activities as managing other people, engineers seldom have organisational authority over the people on whom they rely. Therefore, influencing is a more appropriate description. They draw on a wide

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[38] See, for example, efforts to identify sheep shearing skills in order to replicate these skills with a robot, described by (Trevelyan, 1992).

range of knowledge, much of it carried in the minds of the people involved in the enterprise, as well as external stakeholders.

These responsibilities and the need to influence other people explain why engineers predominantly engage in group 3 activities, social interactions with other people. These can be synchronous, as in face-to-face conversations in meetings, phone calls or video teleconferences, also known as virtual meetings. Asynchronous interactions take place via recorded messages or videos, email or text messages, exchanging documents, or through information systems containing human-readable data such as customer relationship management, maintenance management, project management, change management, or quality management systems. Asynchronous interactions can sometimes be separated by extended time periods, for example, when engineers search for information in documents that might have been prepared decades earlier.

Group 2 activities by engineers, cognitive interactions with abstract objects, usually represented in computer systems, are much less significant in terms of time. Few engineers spend more than 20% of their time on group 2 activities, and for many engineers the proportion of time is less than 5%. Engineers rarely engage in group 3 hands-on activities.

Once we recognise that engineering work mainly consists of interactions with other people, we can appreciate that communication skills are simply the enabler for collaboration performances that requires complex socio-technical interactions to gain conscientious collaboration and influence. Overwhelmingly, engineers communicate with others to coordinate work, engage willing collaboration by others within an agreed timescale, to advocate for resources and particular understandings, and to negotiate with multiple stakeholders, to name just a few aspects of engineers' work reported in the literature.

While many engineers see their social interactions as 'non-technical', and 'not real engineering work' research findings show that these interactions mostly involve or require specific technical knowledge. One of the intriguing research findings demonstrated that the predominance of time spent interacting with other people varied little with career progression. This was contrary to the often-expressed notion that early-career engineers spend more time on technical analysis, and graduate into management and supervisory roles later, increasing the need for social interactions. The notion of distributed knowledge and expertise helps to explain this observation. Knowledge needed by engineers is distributed among the people in the larger enterprise, including clients, contractors, and often local community members. In other words, engineering knowledge exists more as a social network, and engineers traverse their social and professional networks to access that knowledge. As often as not, access to knowledge requires gaining the willing and conscientious collaboration of others to contribute their knowledge through one or more skilled performances. This has become known as technical coordination, and seems to take around 30% of the time of engineers. That is why researchers refer to these interactions as 'socio-technical' interactions.

Unlike engineers and technicians, technologists mainly engage in group 2, interacting with abstract objects through information systems. For example, drafters, programmers, and plant operators in a control room engage mainly in cognitive work. Naturally, social interactions are also critical in collaborative work by technologists. However, sometimes technologists and technicians deliberately minimize social interactions in order to be able concentrate on their work when relying on short-term memory. Interruptions from other people can significantly interfere with short-term memory, requiring additional time to restore focus and pick up the work from the time of the interruption. Worse, interruptions can lead to mistakes, sometimes requiring a procedure to be repeated from the beginning.[39]

Like technicians, technologists also develop knowledge and skills through years of supervised and independent practice. They also develop extensive knowledge of relevant industry standards and practices. Drafters, in particular, develop the ability to represent engineers' ideas in ways that technicians, tradespeople, contractors and suppliers will readily understand. Programmers develop knowledge of particular coding practices that result in efficient development, testing and execution. Plant operators acquire the abilities to sense abnormal

[39] (Stephen R Barley & Bechky, 1994) observed this behaviour in studies of highly skilled science laboratory technicians.

operating conditions and how to compensate for them, as well as being able to safely operate complex systems in abnormal circumstances such as startup, shut down, and emergencies.

Observing activities that dominate work helps to distinguish the three occupations in the accords represented by the IEA document:

> Engineering technicians mainly perform group 1 hands-on activities manipulating physical objects and tools.
>
> Engineering technologists mainly perform group 2 cognitive manipulations on abstract objects in drawings or computer systems.
>
> Professional engineers mainly engage in socio-technical interactions with other people. (Note that in this document, when I refer to 'engineers', I am referring to professional engineers unless otherwise stated.)

This method for distinguishing engineering occupations demonstrates their complementary roles and contributions. With some exceptions such as computer software and engineering compliance reviews, any engineering undertaking requires collaboration and knowledge sharing involving all three occupations. Even the vast information technology industry, predominantly requiring involving software engineers and programmers, still requires phones, computers, optical fibres, cables, communication towers, even the ubiquitous phone technician that replaces a cracked touch display screen.

10.7.1 Design

There is a widely held view, particularly among many engineering faculty, that design is one of the central activities for engineers. Many faculty would agree that design is a special form of technical problem-solving under operational and resource constraints, with some acknowledging the presence of uncertainties and the use of judgement and heuristics to bridge gaps in scientific knowledge.[40] Research studies show that while some engineers are

[40] (Koen, 2009; Purzer, Moore, & Dringenberg, 2018; Quinlan, 2002; Sheppard, Colby, Macatangay, & Sullivan, 2006)

involved in design, much of the design work is handled by specialist designers. They interpret outline requirements and sketches from engineers, architects and product designers and their activity profile more closely aligns with technologists, spending much of their time interacting with CAD models using computers. Specialist designers have more intimate and detailed knowledge of contemporary practice and standards in their areas of practice than many engineers. While engineers interact with clients, project owners, suppliers, factories and specialised contractors, they are more concerned with establishing the design and performance requirements.

10.7.2 Problem-solving

Research studies help to demonstrate that problem-solving itself is quite different from the kinds of activity imagined by engineering faculty. Often, problem-solving starts with a combination of advocacy and negotiation. The first challenge is to convince influential actors, senior engineers, owners, clients and others, that there actually is a problem and it needs solutions. Particularly when multiple disciplines or stakeholders need to be involved in finding solutions, many people react by denying the significance of the problem because they don't want to have to divert precious time and resources. [41] Often, the quickest path to a solution is to find someone who has already solved similar problems.[42]

In the IEA accord definitions, engineers occupy a superior position intellectually, solving *complex* problems, technologists solve *broadly-defined* problems, and associates solve *well-defined* problems.

Here we encounter a fundamental difficulty. All of us solve problems as we go about our daily lives, whether it is planning the fastest means of getting to work when we are running late, finding an appropriate parking space for one's car, or deciding how to balance family desires, needs, the availability and shelf lives of ingredients, family finances, and proximity and opening hours of stores in providing an evening meal. Research helps to demonstrate that,

[41] (Itabashi-Campbell & Gluesing, 2013)

[42] (Jonassen, 2002; Korte, Sheppard, & Jordan, 2008)

while engineers do solve complex technical problems on occasions, this can be a relatively rare occurrence. Engineers have to solve problems involving people, regulations, schedule constraints, logistical constraints, finance and technical issues more frequently. Experienced engineers develop the ability to avoid complex technical problems without obvious solutions because they introduce unwanted uncertainties.

Therefore, the difficulty in distinguishing between occupations here arises from the difficulty in distinguishing *complex* problems that only engineers can solve, from *broadly-defined* problems that technologists can solve, from *well-defined* problems that technicians can solve.

For these reasons, relying on identifying the complexity of problem-solving to distinguish engineering occupations from each other can be unhelpful, because an attribute such as complexity is hard to characterise.

10.7.3 Span of influence

One indicator that can help distinguish professional engineers from technologists is the extent to which an individual influences the actions and/or thinking of other people. Engineers typically have a broad span of influence extending well beyond their immediate work-group. Research reveals engineers as influencers: the results of their concepts, thinking, analysis and calculations influence the actions and thinking of other people who contribute to the engineering process that transforms engineering concepts and ideas into tangible artefacts, systems, processes and infrastructure. Engineers rarely have their hands on tools: instead they influence the actions of other people who do, or the thoughts of investors who commit the immense financial resources needed for engineering projects. Sometimes the influence pathways are tenuous and indirect, as with expert reports written by engineers that later influence government policy or deliberations in law courts. Technologists, on the other hand, tend to have more direct and localised influence, more on systems than other people. For example, plant operators might be controlling complex refineries, process plants, power systems or railways. Sometimes this is direct through computer control systems, and sometimes by issuing instructions to other people: operators or technicians with their hands on valves, levers, knobs or keyboards.

Naturally, technicians and technologists influence others in their peer groups, and engineers, by providing advice, feedback and suggestions, especially when in supervisory roles such as production supervisors, site foremen. Experienced technicians and technologists can be very effective guides and mentors for early-career engineers.

Engineers carry some critical responsibilities that technologists and technicians rarely have on their shoulders. The responsibility to ensure safety, efficacy and minimal environmental disturbance ultimately lies with engineers through the governance of design.[43] Engineers usually have appropriate knowledge grounded in the sciences and mathematics to foresee consequences of decisions and actions far into the future: an essential capability to manage these responsibilities.

Engineers also have the knowledge and intellectual skills to assess technical risks: foreseeable yet uncertain and unpredictable events that influence the behaviour of people and physical artefacts and systems, with either positive or undesirable consequences. It is worth noting here that the thinking styles of many engineers, typically convergent linear thinking and logic, can sometimes blind them to risks that are obvious to others. Smart engineers draw on many different people to identify risks, and then apply their analytical skills to evaluate the likelihood and consequences.

Another influencing role performed by engineers is helping to manage the perceptions and expectations of regulators and stakeholders. This is particularly important in their local communities among whom engineering enterprises develop their social licence to operate, an informal, implied consensus that the operations of the enterprise are acceptable to the community. Most engineers are treated with respect by community members. However, in the face of community antagonism, there can be an instinctive resistance to accepting the views of engineers, so other people are often needed to help overcome that resistance.

Many engineers, particularly in Western cultures, carry significant financial and management responsibilities in their organisations and work-groups. Engineers are often asked to predict

[43] (Magarian & Seering, 2021)

technical and financial performance of systems and artefacts to build a case for investment. Many engineers also carry the responsibilities for meeting financial, delivery and operational targets.

11 Learning Engineering Practice – A New Edition

Over the last few months, I have been writing the second edition of my book Learning Engineering Practice. The revisions have been extensive: about 60% of the text will be new. As part of that effort, I have redesigned an important component of the book: a checklist of engineering practice concepts and activities. This represents a move away from individual competencies and places much more emphasis on the engineering organisation. Current research evidence points to the supporting organisation as the primarily influence on the capacity of an individual engineer. The new edition should be out later this year.

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