

# Guide for Value Generation in the Engineering Enterprise

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## Introduction

Until recently, engineering value creation has mostly been associated with innovation, entrepreneurs, and famous inventors like Thomas Edison and Nikola Tesla.

However, our recent research demonstrates this understanding is misleading. For a start, neither Edison nor Tesla were engineers.

It is the routine, everyday engineering performances dominating the lives of most engineers that contribute most engineering value. Innovation and entrepreneurial activities are important for only a few engineers.

Ultimately, value generation is about productivity improvement, something that needs to be at the forefront of engineering education. Engineers enable people to be more productive: to be able to do more with less time, less effort, less material resources, less energy, less uncertainty, less health risk, and less environmental disturbance. That description also reflects the essential elements of sustainability and climate action.

Routine everyday engineering not only creates great value, but also protects accumulated value from inadvertent destruction.

This document is a guide to engineering value generation for students, educators and practicing engineers. Sections 1 to 9 are addressed to practicing engineers and students while 10 and 11 present guidance for educators. Outline answers for practice questions appear in the text: educators may want to edit the text so they do not appear in a version of these notes provided for students. To facilitate self-study and to enable educators to expand on the ideas presented, we have included some teaching and learning exercises.

This is a living document and our intention is to update it regularly as we receive feedback from educators and students.

Keywords: engineering practice, value creation, engineering education, entrepreneurship

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## 1 Why is Value Creation Important?

What is the value of engineering, the underlying purpose that motivates firms to employ engineers and even engineers themselves? How do engineers add value through their work? There are and have been different answers depending on time and place, and they range from nation building to individual economic opportunity to a desire to make the world a better place.<sup>1</sup> With private firms employing most engineers today, it is concerning that neither engineers nor educators seem to have clear answers.

We have researched engineering practice extensively and found that very few engineers working for private firms can fully and clearly explain the economic value arising from their work.<sup>2</sup>

There is scant mention of this issue in texts that introduce students to engineering. Many students struggle when asked, what's the value contributed by engineers? Typically they will respond hesitantly, uncertain of their responses: "Invent new things?" "Make the world a better place?" and often "Solve problems!"

It is perverse, perhaps, that these same students have no such difficulty explaining the value of being a doctor: "Save lives" "Heal sick people" "Help people live longer and healthier". Or a lawyer: "Get people out of jail" "Provide justice, human rights".

We provide some answers for these questions, and also for these ones too:

- Why is understanding value so important?
- What does value mean in the context of engineering?
- Why is it important to understand how value is created in engineering?

Value creation is the reason why private investors and governments spend so much money on engineering work.

First, by understanding value creation, you will get a job more readily and understand how to keep your job and not get laid off when the next recession comes along in your industry.

Second, by understanding how value is created, you will learn to create value more effectively, helping your employers and clients. If you do it consistently, you will be well rewarded in your career.

Our research has suggested that many engineers have little idea on how value is created, and many are frustrated that their employers don't pay them enough or give them rewarding work. You can avoid most of these frustrations if you learn how to create value.

Creating social value is equally important as economic value, and social is created in similar ways. Through studying these ideas you will learn how to create greater social value and support your own and other human societies.

## 2 Interpretations of value in contemporary literature.

The word "value" is especially challenging for engineers because it has many interpretations, far beyond the comfort of a calculated number in a spreadsheet or an instrument reading. For example, the concept of "net present value" (NPV) would be familiar to those who have studied conventional engineering economics.

One interpretation refers to a virtue based in an ethical position, an abstract notion of what is held by an individual to be intrinsically good, such as honesty.<sup>3</sup>

Extending from this interpretation are "values" or "value systems" – frameworks of ideas and moral arguments that broadly motivate human actions.<sup>4</sup> These may be based in a particular religion or derived from moral philosophy arguments about what it means to be a good person. For example, some people may be motivated by the idea that accumulating wealth is virtuous because it empowers a person to perform good deeds for others, such as philanthropy. Others may shun wealth accumulation, arguing for example that "money is the root of all evil". Others may be motivated by empathy and caring for others.<sup>5</sup> Individual

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<sup>1</sup> (Downey & Lucena, 2004; Lucena, 2010)

<sup>2</sup> (Trevelyan, 2014; Trevelyan & Williams, 2018a, 2018b; Williams & Figueiredo, 2013)

<sup>3</sup> (Fernandes, 2004)

<sup>4</sup> (Bégin, 2018, p3)

<sup>5</sup> (e.g. Hess, Strobel, & Pan, 2016)

engineers, like anyone else, will identify with different value systems, possibly leading to contested ideas on ethics in a given community.<sup>6</sup>

Our focus is on a second interpretation. ‘Value’ describes a measure of ‘goodness’ in an object, an activity, or even a person, for example to describe the value of a theory contributed by a philosopher, or the monetary value of goods or services.

Ng and her colleagues explained in the context of engineering service delivery that value is not an intrinsic property: like beauty, it depends on the perceiver(s), and arises from a conscious human experience.<sup>7</sup>

Value, therefore, can only be **co-created** through the experience of the beneficiary on accepting the provider's value proposition. This value is referred to as **use-value** reflecting the importance of human experience that gives rise to the subjective perception of value.

The business literature has a natural tendency to focus on the more easily observable **exchange-value**, money or other goods exchanged in return for an entitlement to an object or service. The decision by the beneficiary to exchange money or goods is motivated partly by the anticipated use-value (including tangible benefits) and partly because the anticipated risk that the anticipated use-value will not match expectations is believed to be sufficiently low. Kahneman and Tversky referred to this as **decision-value**.<sup>8</sup>

With three such diverse meanings in English, there is plenty of space for confusion.

As would be expected, value creation has received extensive attention in the business research literature particularly since Michael Porter's exposition (1985) of the value chain concept. He described value creation in terms of the price difference between a firm's products or services and all the inputs needed to produce them and argued that superior value creation provides firms with a competitive advantage. Interestingly, there are many different interpretations about value creation in the business literature.<sup>9</sup>

*Practice Question: Find quotations that provide examples of these three different broadly used interpretations of the word ‘value’.*

*Sample Answer: a) “Here are the values that I stand for: honesty, equality, kindness, compassion, treating people the way you want to be treated and helping those in need. To me, those are traditional values.” Ellen DeGeneres (<https://www.brainyquote.com/topics/honesty>).*

*b) “A sudden reduction in the value of certificates upon which solar subsidies in Australia are based has resulted in some solar companies needing to re-issue recent quotes.” (<https://www.solarquotes.com.au/blog/stc-prices-solar-subsidy-mb0133/>)*

*c) “Unlike the FSR or photocell sensors we have looked at, the TMP36 and friends doesn't act like a resistor. Because of that, there is really only one way to read the temperature value from the sensor, and that is plugging the output pin directly into an Analog (ADC) input.” (<https://learn.adafruit.com/tmp36-temperature-sensor/using-a-temp-sensor>).*

## 2.1 Ordinary everyday engineering is what most engineers do

Engineering is a large component of any advanced industrialized economy. In the UK for example, engineering sectors in 2014 contributed 27% of GDP and employed 5.5 million.<sup>10</sup> Private and government sponsored innovation and research (including sciences) was only 1.6% of GDP, so innovation and R&D work employs only a minority of engineers.

The norm is ordinary everyday routine engineering, even in an advanced industrialized economy.

Even though the majority of engineers are not innovating, they must be creating value. The marginal revenue productivity theory of wages in labour market economics predicts that, in a relatively unconstrained labour market, remuneration reflects value added. If some firms had discovered that engineers did not add value to company operations, they would have stopped employing them. Then, with rising profits, other firms would quickly find out and follow, leading to a collapse in engineering employment. That has clearly not happened.

<sup>6</sup> (Davis, 1998)

<sup>7</sup> (Ng, Parry, Smith, & Maull, 2010)

<sup>8</sup> (Kahneman & Tversky, 1984)

<sup>9</sup> (Trevelyan & Williams, 2018a)

<sup>10</sup> (Kumar, Moss, & Johnson, 2016, pp 1, 58)

How then do most engineers create value in ordinary engineering practice where innovation is not a priority and may even be avoided?

Until we performed this research there were few answers. Here we aim to provide you with answers that will help you in your careers.

## 2.2 *Value creation motivates investors*

We have explained that value, as a measure of perceived goodness in an object or service, is not only subjective but also co-created by the perceiver and the provider and therefore cannot be observed directly.

Exchange-value, payment for entitlement to an object or service, can be observed but can only serve as an indirect measure of the anticipated use-value (or decision-value) that motivated the exchange for the provider and beneficiary and other parties involved.

All engineering requires investment of resources by a firm or social institution long before the benefits can be experienced.<sup>11</sup> Therefore we can infer that it is mostly the anticipated benefits and risks that motivate investors to contribute financial and other resources (the actual amount represents exchange-value). Apart from investment decisions, repeat business can also provide an indirect measure of investor decision-value.<sup>12</sup>

Engineers' contributions to value creation, therefore, are closely related to actions that influence investor (or client) expectations of benefits and risks. Improving these expectations, therefore, is likely to provide a higher exchange-value.

Along with forecast benefits, investors perceive most engineering investments to have intrinsic downside risks, partly because the investors may have little understanding of technical aspects of the engineering work, and partly because many investment decisions rely on commercial forecasts based at least in part on engineers' data. Investors, therefore, have to place their trust in engineers to deliver expected outcomes. This trust is usually developed through extensive face to face encounters over a long period of time. That is why networking is such an important activity for engineers and business people: these social encounters all contribute (hopefully) towards building trusting relationships.

The tall buildings that characterize modern cities help to demonstrate the necessity of face-to-face social encounters. These buildings enable a large number of people to live and work in close enough proximity to facilitate face-to-face encounters more often than would otherwise be feasible. It is no surprise, therefore, that these extremely expensive structures have real value for the people who occupy them. It is easy to spot the financial districts of major cities because of the tall buildings needed, ultimately, for trust-building.

Investors attach greater value to less risky investments.<sup>13</sup> Therefore, reducing the downside risks *as perceived by an investor* increases the exchange-value (total investment) that the investor is prepared to pay, resulting in value creation.

Figure 1 illustrates typical personal investment decisions, ranging from buying a home through to playing poker machines. Most people think houses are much less risky investments than shares, for example. Education is also seen as a low-risk investment.

Figure 2 helps to demonstrate that similar ideas motivate commercial engineering investments. In this hypothetical example, the engineer's risk perception is low because the engineer knows how to avoid uncertainties. A typical investor sees the same concept as inherently risky because they probably understand little of the technical side of engineering, and many have had, or heard about bad experiences with engineering investments in the past. Most investors will suspect that the investment will require much more money than the engineer has forecasted.

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<sup>11</sup> (Trevelyan, 2014, p. p.373)

<sup>12</sup> (Drake, 2015)

<sup>13</sup> (Kahneman & Tversky, 1984)

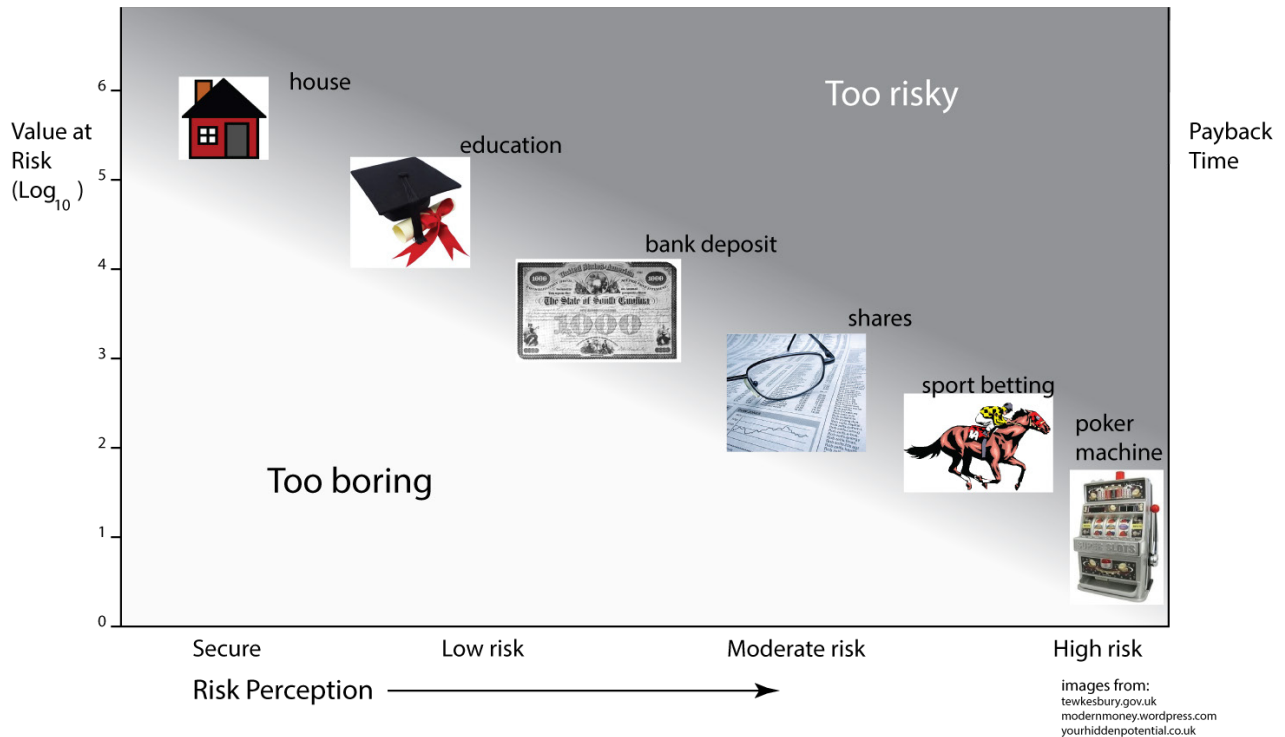


Figure 1: The magnitude of a typical personal investment decision decreases with increases perceived risk. Furthermore, the acceptable delay (payback time) also decreases with increasing risk. That’s why poker machines are attractive for many people because they provide almost instant payouts when you win.

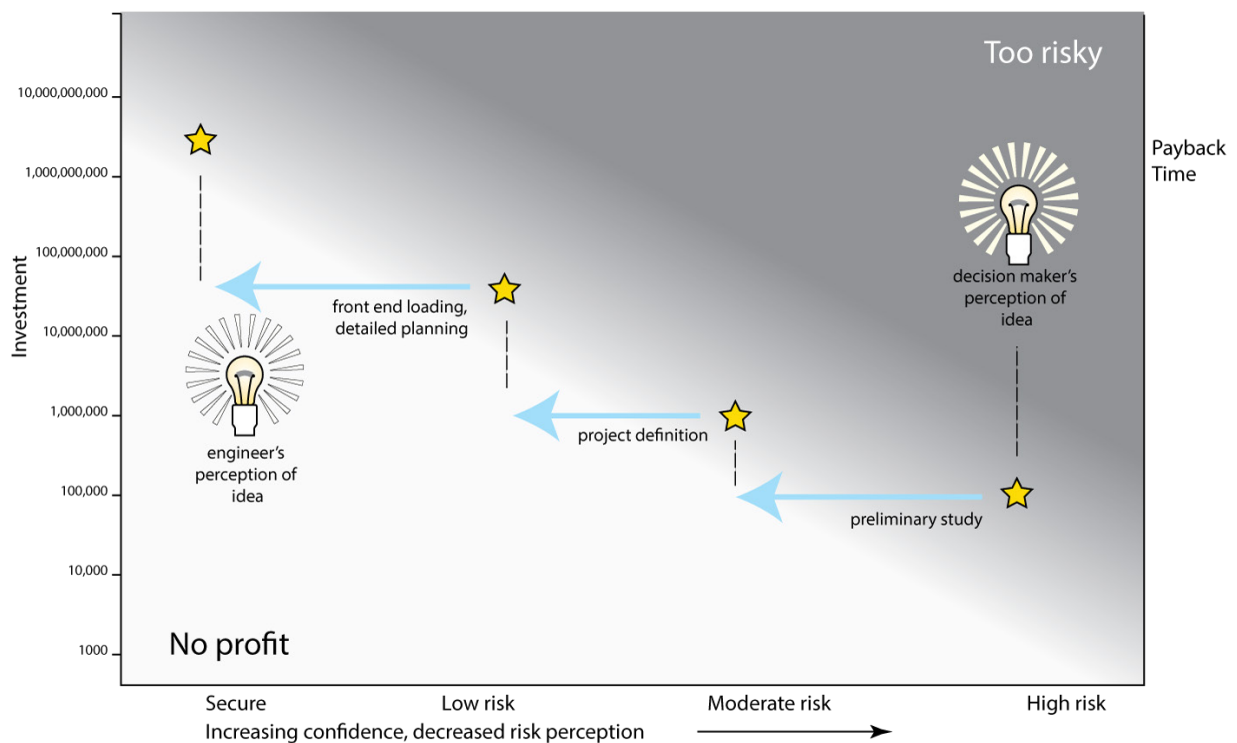


Figure 2: Commercial and engineering decisions are characterized by a series of intermediate decisions, each leading to a more detailed investigation that reduces the perceived investment risk.

Therefore, a series of preparatory studies precedes a multi-billion dollar investment decision. This example starts with a feasibility study costing around \$100,000. If the results are favourable, the initial high risk perceived by the investor will have been reduced by eliminating, or least reducing the largest uncertainties. A project definition study follows, costing around ten times the feasibility study. This is where engineering

technical analysis typically starts with the development of computer models to calculate the likely performance and financial returns from the proposed investment. Again, if further uncertainties are reduced sufficiently, the next step would be front-end loading and detailed planning, the preparation of thousands of detailed documents describing how all the major issues with the project will be handled. This activity clears the way for the final investment decision to proceed with spending billions of dollars. Figure 2 only shows three stages for simplicity – in reality there might be four or five stages preceding such a large investment decision. Each stage brings the venture from the darker zone of unacceptable risk back towards a more acceptable risk, justifying a larger investment for the next stage.

Most large firms will have many projects simultaneously developing through these stages. At each stage, more risky projects will be rejected and either delayed or abandoned entirely. That is why many engineers work on project investigations that ultimately seem to lead nowhere because the project owners or investors choose more attractive projects. The value in these studies for the investors is risk reduction and better information helping them make safe investment decisions, or so we would hope. Chapter 11 in “The Making of an Expert Engineer” describes these financial decisions in much greater detail, and explains some of the flaws and failures.

That is why we see the activities performed by engineers in these investigations as adding value, such as increasing forecast benefits, or by reducing perceived downside risks.

Of course, there can be an indirect contribution to value creation. If the investors’ experience turns out to be better than expected, it is more likely to result in repeat business for later projects. Greater financial benefits could motivate another investor to purchase the project (or a share in the project) for a higher value, providing a profit to the original investor. However, value is ultimately associated with *subjective perceptions of the experience* which are co-created. The subjective experiences perceived by investors can be influenced by many factors beyond financial benefits, such as the quality of interpersonal relationships associated with a venture.

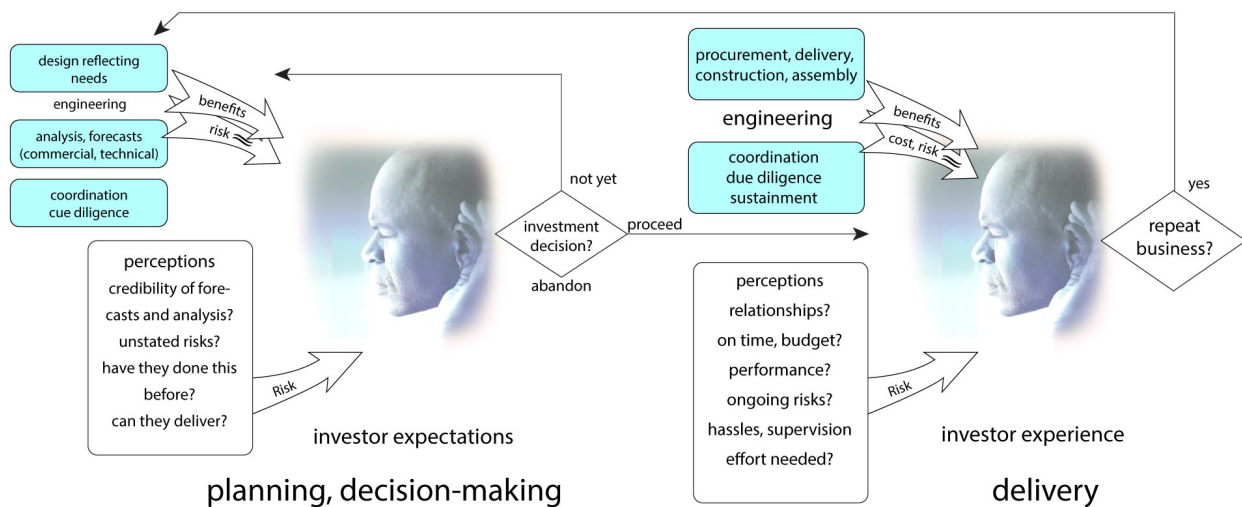


Figure 3: Investor expectations, decision making and experience

Figure 3 summarises these ideas. Investors engage engineers to understand their firms and society needs, and devise solutions that meet those needs. Engineers forecast the technical performance of these solutions and estimate financial benefits over time. This work requires extensive collaboration and due diligence as explained later.

Note that we use the word ‘performance’ in this guide with two distinct meanings.

*A human performance* refers to a series of actions by a person, usually interacting with several other people, for example coordinating technical work performed by others.

*Performance of a product or system* refers to observable attributes of the system by which engineers judge its utility. For example, the fuel economy of a car is one aspect of its performance. Frequently



we distinguish between technical performance (e.g. time to accelerate to 100 kph), and commercial performance (e.g. selling price of the car to retailers).

An investment decision is strongly influenced by perceptions such as the credibility of the engineers' forecasts and expectations of future changes in the economy. Investors will ask whether the engineers have experience of similar work before, and whether the technology has worked on previous projects. They will come to some intuitive understandings on how well the engineers can deliver the expected results.

Depending on these perceptions, the investors will decide either to proceed with the project, or ask for more analysis and forecasting, work which will still need money to be invested of course, but not as much as the final investment decision to proceed (FID). They may decide to abandon the project, of course.

Once they decide to proceed, investors will experience the results of the engineering work as it proceeds. Ultimately, if their experience is good, they may well decide to make another similar engineering investment – we call this repeat business and that's good for us engineers.

Investors' experience will be shaped by several factors. Did they have good relationships with the engineers? Many firms are successful because they count investors as personal friends as well as business partners. Did the cost increase? Was the work completed on schedule? Does the finished plant or equipment perform as expected? Are the users satisfied? Are there ongoing risks in using it? Perhaps above all, was it a satisfying experience without undue hassles and difficulties, disagreements and conflict? All these factors influence whether investors come back for repeat business.

### 3 Project life cycle model<sup>14</sup>

This paper focuses attention on investment decisions in engineering projects. We will explain the context for these decisions. Most engineering projects follow a similar sequence from the first ideas conceiving the project until it is finally decommissioned.

1. At the start, engineers attempt to understand and at the same time shape clients' perceptions of their needs, and work with clients to articulate requirements. Helping the client to see their issues in terms of engineering possibilities is part of an engineer's work. Gaining clients' and investors' trust and confidence is essential because much of the money will be spent and much time elapses before anyone gains benefits and money is repaid to the investors. Engineers also sustain their own businesses by helping clients anticipate future needs for their services.
2. Engineers conceive different ways to meet requirements economically, propose solutions using readily available components, and design special-purpose parts when needed. Much of the design work involves re-arranging elements drawn from a vast memory of design fragments and piecing them together.<sup>15</sup> Engineers solve technical problems when necessary, though most engineers aim to avoid technical problems as much as possible through a combination of shaping client expectations, foresight, experience, following well-established standard approaches, careful planning, and effective organizational methods.
3. Engineers collect data and create mathematical models based on scientific knowledge and experience to analyze and predict technical and commercial performance of different solutions so that sensible choices can be made. The level of precision depends on investors' acceptance of risk and uncertainty. Engineers usually describe uncertainty qualitatively, occasionally quantifying it, accounting for incomplete data and uncertainty in available data and from external uncontrolled events. They also diagnose perceived performance deficiencies (or failures), conceive and design remediation works, and predict how well the modified system will perform. They also negotiate for appropriate approvals from regulatory authorities.

These investigative steps may be repeated with progressively more certainty, particularly in large projects, until prediction uncertainty can be reduced to match investors' expectations.<sup>16</sup> The term "engineering problem-solving" is often used to describe these investigations.<sup>17</sup>

<sup>14</sup> Comprising material reproduced from (Trevelyan, 2010) and (Trevelyan, 2014, Ch3)

<sup>15</sup> Appropriate structural elements described in Gainsburg (2010a); also in other disciplines (Sonntag, Niessen, & Volmer, 2006, p377)

<sup>16</sup> Often referred to as a project phase gate decision process (Cooper, 1993, p109).

<sup>17</sup> E.g. "The Engineering Method" (Dowling, Carew, & Hadgraft, 2009, Ch3).

Using the engineers’ predictions as a starting point, the client, investors, regulatory authorities, and contractors decide whether to proceed with the project. The work up to this point is often called “front end engineering.” Up to this point, only 5-10% of the overall project budget will have been spent on the investigations described above. Once the final investment decision is been made, much more has to be spent in the ‘project execution’ phases that follow:

4. Engineers prepare detailed plans, designs, and specifications for the work to be performed and organize the people and resources that will be needed for construction, commissioning, operations, and maintenance.
5. Engineers coordinate, monitor, and evaluate the work while it is being performed, adapting plans and organization to circumstances, explaining what needs to be done, making sure that the work is performed safely, to an agreed schedule, within an agreed budget, and within negotiated constraints such as regulatory approvals, effects on the local community, and the environment. Although engineers carry these responsibilities, they are reluctant to use formal authority (and it is only rarely available to them). Instead they rely on informal technical coordination. The aim is to deliver the intended products and utility services with the predicted performance and reliability.
6. Engineers conceive, plan, organize, coordinate, monitor, and evaluate decommissioning, removal, reuse, and recycling at the end of a product's life span, and also the rehabilitation, remediation, and restoration of the site and the local environment.

Since engineering is a human performance, we need to accept that the performers have unpredictable aspects, like nature. Given that the aim is *predictable* delivery of *reliable* products and services, engineers need to know how to ensure that *unpredictable* aspects of countless individual performances produce results in a *predictable* way. Assessing risks and uncertainty, checking and review, technical standards, organization, training and procedures, coordination and monitoring, survey and measurement, teamwork, configuration management, planning, testing, and inspection are all parts of an engineer’s repertoire for containing human and natural uncertainty.

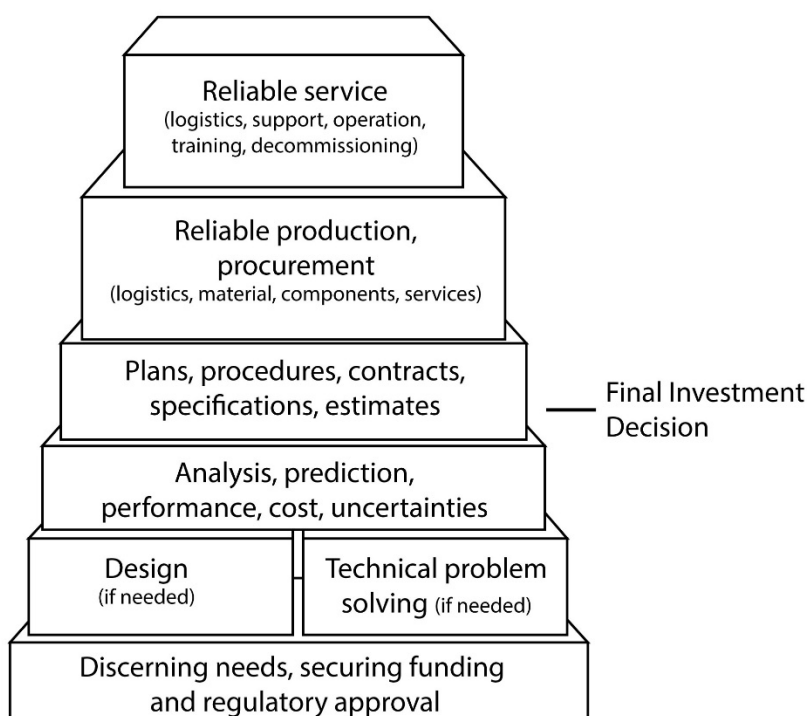


Figure 4: Main sequential stages in an engineering project, starting from the bottom, explained in the text.

Different engineering ventures naturally place different emphasis on each of the stages. For example, in the context of an engineering consultancy the ‘product’ is usually information, one or more technical reports. The ‘reliable service’ stage of the project may only involve some seminars or workshops to explain the contents of the reports to the people who need the knowledge provided by the consultants. For a construction design firm,

plans and specification documents may be the product, while construction supervision may be an optional service. Plans, procedures, contracts, specifications, and estimates would be part of the product.

Detailed planning and preparation of all project documentation is usually the last step before the critical final investment decision is made. Typically, by the end of this stage, between 5% and 10% of the project budget will have already been spent. From this point, everything gets much more expensive.

Only in the last step does all this investment start to provide some useful value for people through the tangible products or services provided. This is when payments start to flow back to the investors who provided the funding for the venture. The product has to work reliably for its expected service life, and often much longer. Sustainment – operations, asset management and maintenance – plays an important part in achieving this. Sustainment means keeping everything working so that the predicted performance is delivered throughout the service life of the product or process. Ultimately, there will be a decommissioning step when the artefacts<sup>18</sup> are removed for reuse or recycling. In the case of a manufactured consumer product, this can happen at any time during the expected life of the product.

Many engineers work on the early feasibility study stages of projects, before the final investment decision. However, many engineering projects never pass the investment decision point. These engineers spend most of their time working out which of hundreds of possible projects is likely to create enough value for investors.

Many aspects of the work performed by engineers remain invisible and cannot be directly related to the blocks shown in Figure 4. Many of these constitute work that engineers don't regard as 'real engineering'.<sup>19</sup> Figure 3 represents similar activity to Figure 4, but this time we are looking at a cross-section to expose what is not visible in Figure 2. What we see in Figure 4 is only the 'top deck' of engineering practice; Figure 5 shows the other decks that provide the 'structure' without which the top deck would never remain intact. The proportional sized of the different 'decks' correspond to the relative amount of effort required, based on what we have observed from numerous case studies. Like an iceberg, these invisible engineering aspects are much more significant than the top deck. Technical engineering work that you learn about in your engineering degree course represents, at best, only two 'planks' of the top deck.

These 'invisible' aspects of engineering practice have evolved over time to manage all the uncertainties and unpredictable elements of engineering practice that arise from the reality that engineering is a social system that depends on countless individuals and, to some degree, unpredictable human performances.

Many engineers find it hard to even predict their own work. Between scheduled meetings, they react to problems as they occur, so the results from their work will be inherently unpredictable.<sup>20</sup> Engineers report that they can have 60 or more separate, simultaneous, ongoing issues for which they are personally responsible. Many do not seem to have a systematic way to choose which ones to work on each day, or in what order these issues should be handled.

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<sup>18</sup> Artefact – system, infrastructure or product created by human actions

<sup>19</sup> (Perlow & Bailyn, 1997, pp 232–235)

<sup>20</sup> (Trevelyan, 2007, p377)

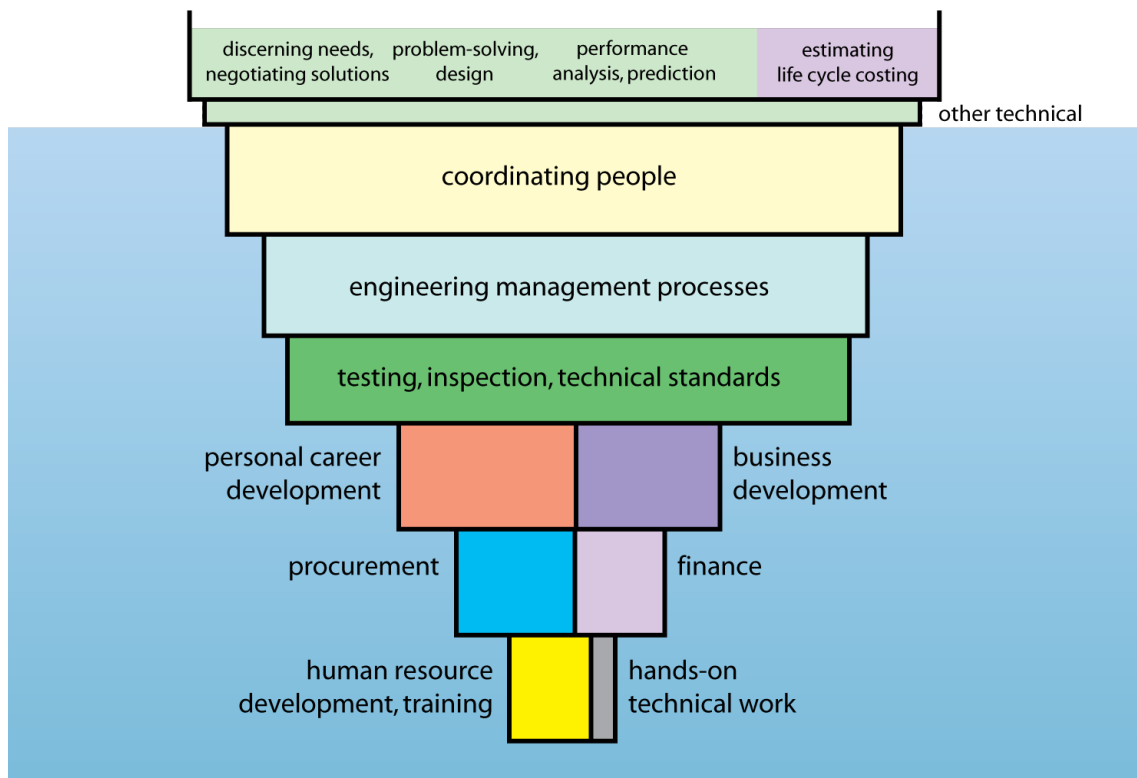


Figure 5: Invisible engineering

Most of these hidden aspects of engineering practice provide a measure of predictability for the end results of individually unpredictable performances by the participants. One of these hidden aspects is helping engineers comply with appropriate technical standards to reduce the chance that mistakes will be made that otherwise would not be picked up in time. Technical standards have been created through the experience of other engineers and are carefully negotiated within each specialised engineering discipline, striking a balance between restrictions to promote safety and ease of use, while also avoiding constraints that would inhibit innovation and design freedom.<sup>21</sup>

The social process by which this expertise is shared contributes a significant portion of the hidden layers in Figure 5 and helps to explain why building relationships with experienced engineers is so critical for engineers that are just beginning their career.<sup>22</sup>

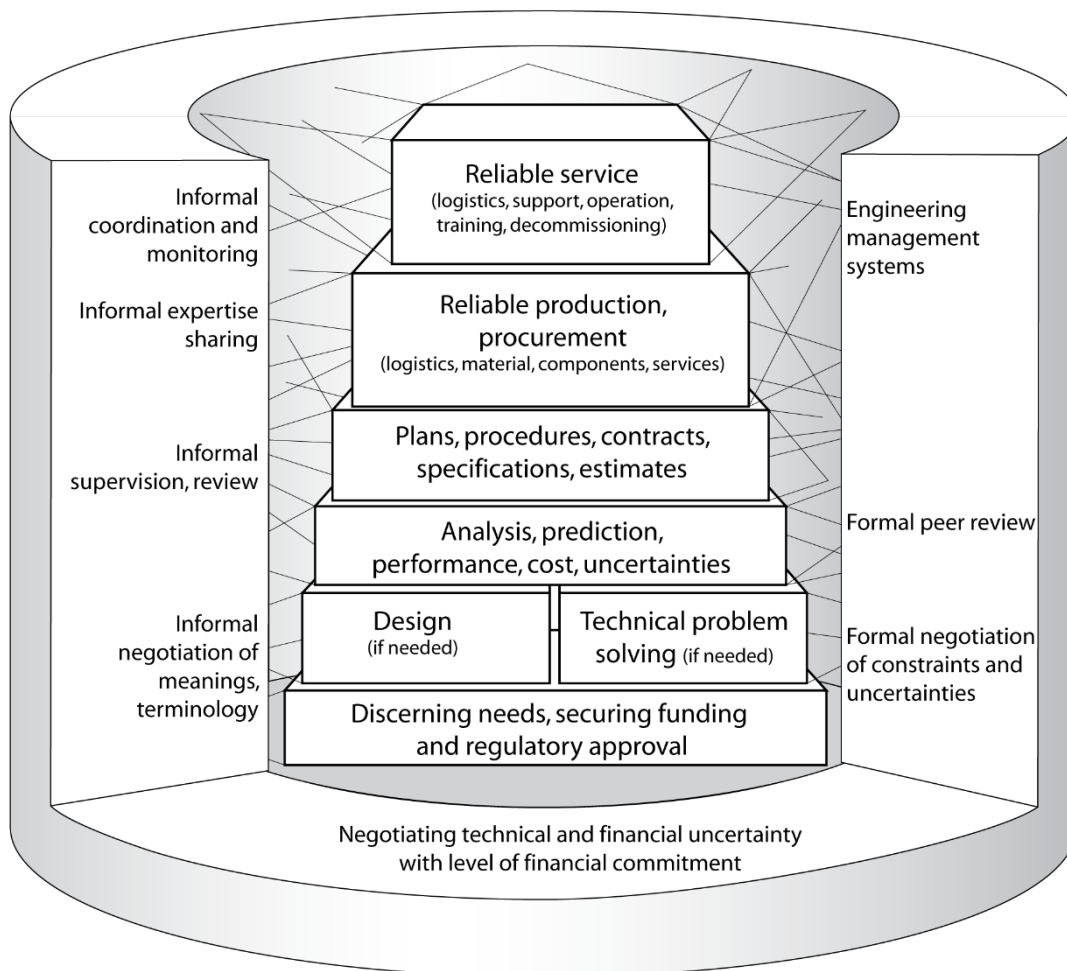
Figure 6 combines the invisible elements of Figure 5 with the sequential life cycle model shown in Figure 4. The stack of blocks representing the life cycle of an engineering project is enclosed within a coordination ring that continually guides the implementation steps towards the intended objectives. A web of social relationships provides necessary coordination and project management for the technical work that all depends on collaborative human activity. The coordination ring helps to produce predictable results from this collaboration, even though each of the human contributions is unpredictable. The coordination ring consists of informal (and often invisible) processes grouped on the left and their formal engineering management equivalents on the right. In a way, the formal coordination processes are also invisible: they are often regarded as ‘non-engineering’ activities.<sup>23</sup>

<sup>21</sup> (Shapiro, 1997)

<sup>22</sup> (Lee & Smith, 1992), this issue is the focus of Section 5.2.

<sup>23</sup> Informal leadership, technical coordination, is described in (Trevelyan, 2007). The significance of technical coordination in US practice is explained by (Anderson, Courter, McGlamery, Nathans-Kelly, & Nicometo, 2010). Invisible aspects of engineering work are also described by (Fletcher, 1999).

On the formal side of the coordination ring, we find engineering management systems, including project management, configuration management, environmental management,<sup>24</sup> health and safety management,<sup>25</sup> quality management,<sup>26</sup> asset management,<sup>27</sup> document management and change management.



*Figure 6: Visual representation of an engineering project. The stack of project steps is surrounded and supported by a coordination ring that guides the project and manages all the uncertainties introduced by human performance. Coordination links with the world outside of a given project also occupy much of an engineer’s effort; these links are not shown on the diagram but are equally significant.*

It is important to note how design and technical problem solving are relatively insignificant aspects in these diagrams. Technical problem solving is actually avoided as much as possible: it is typically preferable to use solutions that have been tried and tested in the past, rather than devising new ones with uncertain efficacy.

This might seem to contradict the emphasis on innovation and invention that underpins many of the ideas we learn about in our engineering education. In this guide we explain how the perceptions of investors who provide the money for us to have fun doing engineering. We will explain why finding ways to avoid the uncertainties associated with innovation creates greater value for investors.

For the same reason, in many projects, engineers reuse designs from previous projects as frequently as possible. Once again, this saves time and reduces uncertainty.

<sup>24</sup> e.g. ISO 14000 series

<sup>25</sup> e.g. ISO 18000 series

<sup>26</sup> e.g. ISO 9000 series

<sup>27</sup> Also known as sustainment, e.g. ISO 55000 series, formerly PAS-55

These diagrams should help you understand how much there is to learn about engineering practice beyond the limited coverage provided in university engineering courses.

Notice how the coordination ring also acts as the foundation for the whole endeavour: this is intentional.

The coordination ring involves continual interaction between all the participants, including the client(s), investors, financiers, engineers, contractors, suppliers, production and service delivery workers, technicians, regulators, government agencies, the local community, and special interest groups.

In the coordination ring base, work starts with negotiations on constraints, even before funds have been committed. Constraints include:

- capabilities of suppliers, production capacity
- technical requirements
- schedule
- regulatory requirements
- health & safety requirements
- environmental impact, emissions
- reliability requirement, client's maintenance capacity
- client's financial capacity
- external financier(s) requirements
- tolerance for uncertainty
- intellectual property

These negotiations provide the decision parameters for investors who commit their funds at each stage of the project.

At the informal level, there is continuous negotiation about meanings and interpretations. Different participants initially attach their own meanings to the terms used to describe every aspect of the project, but as the project proceeds, these differences have to be resolved, or at least understood and acknowledged. For example, there may be differences in the way that specifications are interpreted. Many people think a specification is a non-negotiable statement of requirements: components cannot be accepted unless they pass all tests at the required level of performance. However, others may think this only applies to *production* items. Pre-production versions of certain components would not necessarily meet all aspects of the specification. Some people may understand a specification to be 'elastic', meaning that as long as the essential requirements are met, other non-compliances could be negotiated away in the form of a price discount, if and when they became apparent. In one study, we found that many engineers referred to 'reliability' issues that manufacturers considered to be 'quality' problems. Different individuals involved in the coordination ring construct their own knowledge and understanding in different ways, which can make the process of sharing that knowledge a lengthy and difficult one at times.

#### **4 How do engineers contribute value in an investment decision?**

Figure 7 helps to show how different engineering performances shape investor expectations prior to an investment decision, following the argument presented in section 2.

The exchange-value of a project is represented by the amount investors are prepared to spend. Engineering investigations help investors gain sufficient confidence for their final investment decision, the point at which they are prepared to spend the necessary funds.

Therefore we can say that the engineering investigations have helped create value by increasing the amount the investors are confident in spending. In this section we will explain how engineers contribute to this confidence. Each of the numbered performances in figure 7 is briefly explained in the paragraphs that follow, showing how they contribute to value creation.

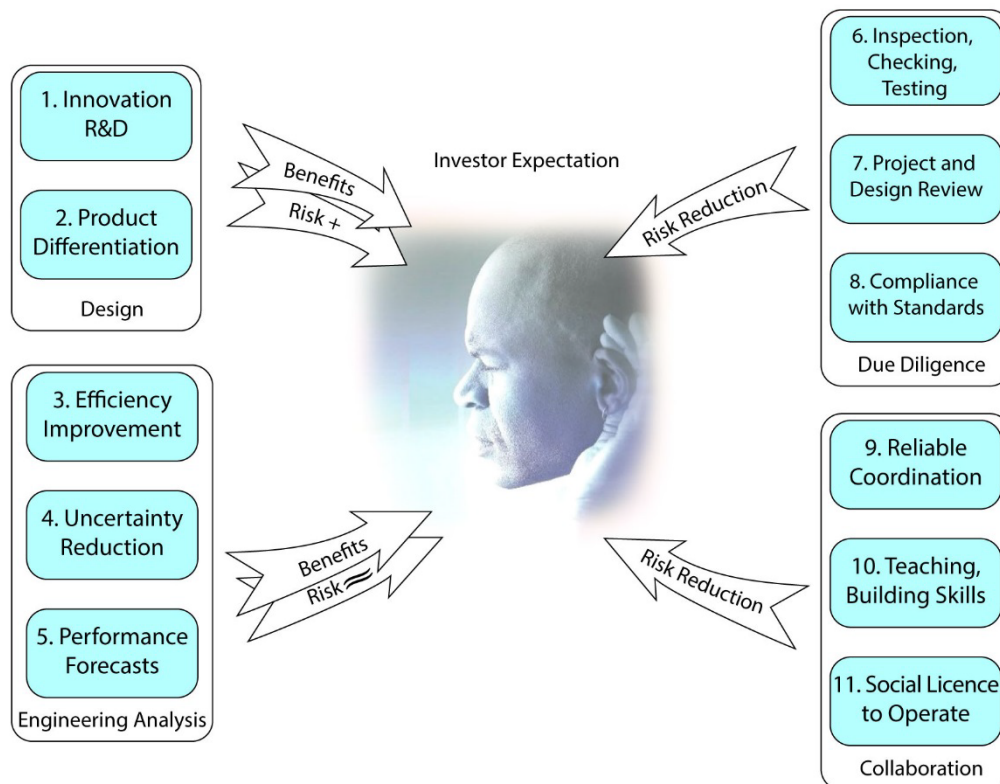


Figure 7: Influencing investor decisions.

(‘risk+’ indicates additional risk perception; ‘risk≈’ indicates quantification of risks and uncertainty).

Some of the following sub-sections provide much more detailed explanations than others, anticipating that students will have better insight and understanding about analysis methods, for example, than technical collaboration performances.

#### 4.1 Value creation from innovation and design

##### Innovation, research and development (1)

Engineers create value through innovation performances such as research, development, experimentation, and intellectual property protection.<sup>28</sup> As explained earlier, only a minority of engineers are engaged in these performances.

Much of the value created by innovations arises from technical and commercial performance improvements. For example, finding a new rechargeable battery material that provides similar energy storage capacity with a lower manufacturing cost enables a battery maker to increase their profits. In this instance, the manufacturer is said to *appropriate* the value created through increased profits.

Another example could be a new battery material that provides similar energy storage capacity with slightly lower manufacturing cost, but greatly extends the service life of the battery, enabling it to be charged and discharged many more times. In this case, the end user benefits because the battery does not have to be replaced so often. The battery maker *may* be able to charge a higher price for the batteries, increasing profit margins. However, if customers are uncertain about gaining any benefit, and are not prepared to pay a significantly higher price for the batteries, it is possible that the end user appropriates most of the benefits.

These examples show how improving performance creates value, and also how the ultimate value created may be appropriated unevenly between different groups of people involved.

In the second example it is possible that, after many years of production, medical evidence starts to accumulate linking the new material *inside* the battery with increased risk of cancer by people using the batteries, even though no earlier evidence of cancer risk could be found when the material was first used in

<sup>28</sup> (e.g. Zhang & Gregory, 2011)

production. Although no government regulation authorities take action, the manufacturers decide to stop production and sales because of the increased cost of product liability insurance.

For these and other reasons, investors often associate innovation with extra risk and uncertainty. Some investors are prepared to accept these risks: venture capitalists specialise in funding innovations and most will find ways to share the risks with other investors, or support many smaller firms working on innovations in the expectation that the majority will fail, but some will succeed.

*Practice Question: Find real-life examples where the value of innovation has been largely appropriated by end users.*

*Sample Answer: Low cost airlines are well-known examples: airline profit margins have remained mostly unchanged, but the cost of flying for many people has been enormously reduced.*

### Product differentiation (2)

By designing products that provide improved buyer and end-user experience (product differentiation) engineers can increase the expected use-value of products and services and often the exchange-value as well.<sup>29</sup>

For example, an attractively designed and packaged product can improve the appearance of the retail outlet in which it is displayed, adding value for the retailer as well as the product manufacturer. Even though the exchange-value (or product price) remains the same, the retailer keeps more product on display in stores, increasing the product sales volume, and also increasing the likelihood that customers buy other products when they visit the stores. In instances where the product is relatively expensive or small and easily stolen, the manufacturer may even supply the retailer with dummy products consisting only of the outer casing, entirely for display purposes.

Customers can be persuaded to pay more for an electric car that has faster charging, racing car acceleration and handling performance, especially if it has subtle decorative features distinguishing it from lower performance models.

A product that can be tailored to a wider variety of user preferences is likely to be purchased by a larger number of people, all of whom have different personal preferences.<sup>30</sup>

*Practice Question: What distinguishes genuine innovation from product differentiation?*

*Sample Answer: One way to distinguish genuine innovation is its patentability. Patents require a genuine “inventive step” to be defined. Even if a patent is granted in a country, if it is subsequently found to have been an “improvement that was obvious to skilled people practicing in that area of technology at the time” it might be declared invalid in subsequent litigation. However, in different contexts, it may be difficult to decide.*

*Practice Question: Visit a local supermarket and search for examples where essentially similar products have been differentiated by their manufacturers in an attempt to appropriate greater commercial value.*

*Sample Answer: Laundry detergents offer plenty of examples, ranging from differences in packaging size, appearance and materials, to different product forms – solid and liquid, and the addition of incidental components such as scents.*

*Practice Question: What forms of intellectual property protection could be used to restrict a competing company from copying a way to differentiate their products?*

*Sample Answer: A trademark is one method: for example, the particular combination of shapes and colours used in a commercial brand logo can be protected through trademark laws. A trademark has to be registered, however, and the registration may be opposed by a competitor. Copyright can be used without the need for registration, but has more limited coverage.*

<sup>29</sup> (Porter, 1985, Ch4)

<sup>30</sup> Appropriate product differentiation and customisation can create additional value (Franke & Piller, 2004; Köbler, Fähling, Vattai, Leimeister, & Kremar, 2009), but excessive customisation can lead to value destruction (Sköld & Olaison, 2012).



## 4.2 Value created from engineering analysis

### Efficiency improvements (3)

By minimising the human effort, materials, energy, and environmental disturbance required to achieve a specified outcome, engineers are directly creating value even if little or no innovation is required to do that. These efforts reduce the direct cost of the outcome, regardless of whether the cost is measured in economic, environmental or social terms. This can be called “value creation through efficiency improvements”.<sup>31</sup>

*Practice Question: Find examples where engineers have reduced each of the following to create value: i) reducing human effort required for a given outcome, ii) reducing material cost, iii) reducing the amount of material needed, iv) reducing energy requirements to achieve a given outcome, v) reducing fossil fuel energy requirement to provide a given level of power output, and vi) reducing the environmental disturbance (e.g. pollution emissions) to achieve a given outcome. In each case, try and assess (in qualitative terms) who appropriated the value of these improvements.*

### Reducing technical uncertainties (4)

Engineers use extensive analysis, calculations and experiments to reduce technical uncertainties. By doing so, they reduce the additional human effort, materials, energy and environmental disturbance needed to ensure a given outcome with a given probability of success. These additional provisions are often referred to as a ‘design margin’, ‘design factor’ or ‘safety factor’.

Consider for example an improved material manufacturing process that provides a material with reduced defects. A smaller design margin could be adopted by using this material because less material is needed to provide the minimum required strength, even in the presence of defects. Reduced material consumption then leads to commercial benefits such as reduced transport cost, creating additional value. We call this value creation performance “value creation through uncertainty reduction”.

Uncertainty reduction also comes from reducing the possibility of human errors in, for example, assembly of parts. If it is possible to assemble parts incorrectly, that will happen from time to time. By designing the parts so it is impossible to assemble them incorrectly, defective assemblies can be eliminated.

*Practice Question: Find one or more examples where engineers have reduced safety factors or design margins by using more accurate analysis methods to predict ultimate performance limits. In each case, try and assess (in qualitative terms) who appropriated the value of these improvements.*

*Sample Answer: For an example, see Duncan, J. M. (2000) “Factors of safety and reliability in geotechnical engineering”, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 126, 4, April, pp307-316.*

### Performance forecasts (5)

Engineers use analysis to prepare forecasts of technical and commercial performance that are sufficiently reliable to justify financial investment, creating value as a result. Engineers can also use similar analysis methods to quantify the risk, reducing uncertainty in the minds of investors.

The speed and accuracy of forecasting has to suit the investment decision. For small investments in feasibility studies or preliminary design, for example, accuracy of 20% will often be sufficient, but there will be little time for detailed analysis. For these decisions, fast and approximate methods are needed. Powerful computational tools such as finite element analysis can yield much greater accuracy but require much more time. Expert judgement is often needed to decide whether more accurate and costly engineering analysis results in greater value.<sup>32</sup>

Much of the time, engineers are expected to provide their forecasts with quantified uncertainty as there are significant uncertainties in data and missing information. Data gaps have to be identified and replaced with justifiable assumptions.

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<sup>31</sup> (Zhang & Gregory, 2011)

<sup>32</sup> (Gainsburg, 2006)

*Practice Question: Find examples where quantitative risk assessment has provided reliable data on which to forecast operational risks. While there are plenty of published research papers that advocate these methods, it is important to choose examples where quantitative evidence of successful forecasting has been provided.*

*Sample Answer: See Bertolini, M., Bevilacqua, M., Ciarapica, F. E., and Giachetta, G. (2009) Development of Risk-Based Inspection and Maintenance procedures for an oil refinery. Journal of Loss Prevention in the Process Industries, 22, 2, March, pp244-253. Note their qualifications on data quality. A lack reliable and consistent data often prevents the application of quantitative methods which is why qualitative risk assessment methods tend to be used instead.*

*Practice Question: Find examples where engineers have provided over-optimistic operational forecasts in response to pressure from project promoters or investors. Suggest ways in which engineers can reduce the chances of this happening, to avoid the possibility of subsequent claims for compensation by other investors who were misled about the commercial forecasts for a project they invested in.*

*Sample Answer: Engineers provided over-optimistic traffic forecasts for major infrastructure projects in Australia, such as the cross-city tunnel in Sydney and the airport link tunnel in Brisbane. Engineers claimed that they were forced to do this in response to pressure from the project owners who were attracting other investors to share the cost of the projects. See, for example, Wiggins, J. (2017) “Airport Link models ‘utterly absurd’”, Australian Financial Review, Friday October 20, p17.*

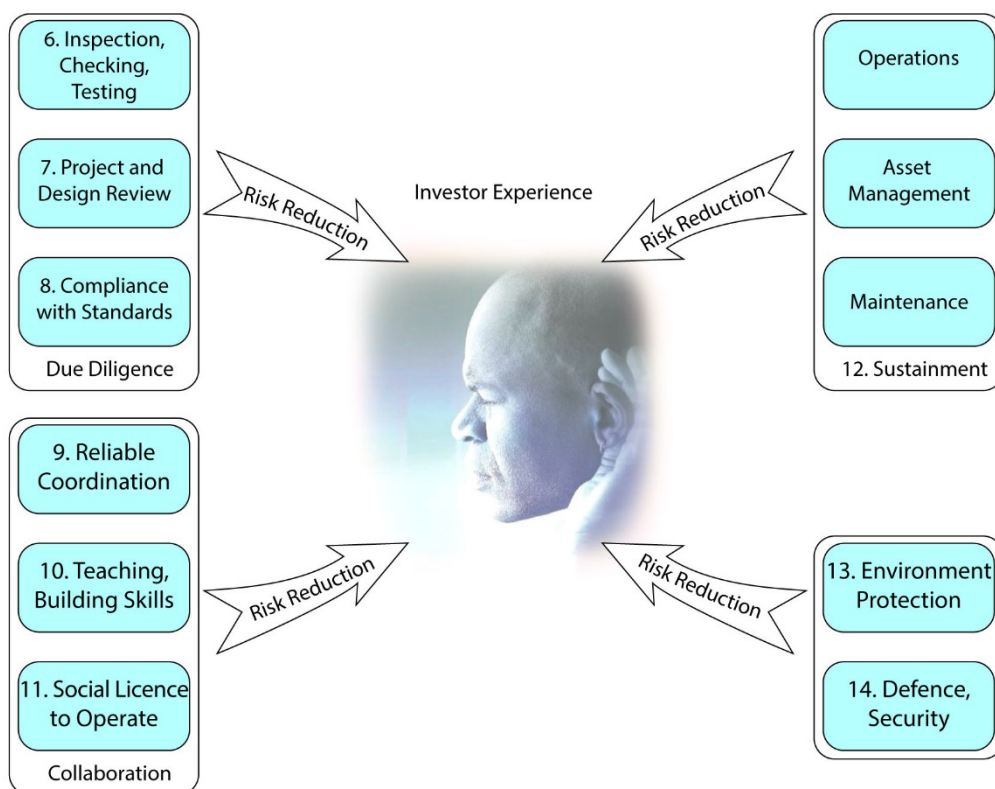


Figure 8: Delivering and protecting value: influencing investors’ experiences.

### 5 How do engineers deliver value?

We have explained how engineering creates value by, for example, producing sufficiently accurate forecasts of technical and commercial performance to build investor confidence, thereby increasing the amount an investor is prepared to spend. Engineering work also helps to *deliver* value by ensuring that a proposed project provides investors, users and societies with real tangible value, rather than *anticipated* value.

Performances 1-5 in the preceding section are just as important in this second and much more expensive phase of an engineering project, after the final investment decision has been made. In the same way performances 6-10 described in this section, are no less important before the final investment decision. However, the major

part of the value created by the performances described below emerges after the final investment decision, when engineers deliver on their promises. For that reason, we describe them as value *delivery* performances.

### 5.1 Value delivery from due diligence

Project and design reviews, checking, compliance with standards, inspections and testing all help ensure that the technical intentions are faithfully reflected in the design documentation and project plans and that performance predictions are trustworthy. Collectively these performances are known as engineering due diligence or quality assurance. They provide reassurance for investors and reduce the actual and apparent risks. Value is being created by these performances because the exchange-value of the project, represented by the funding that investors are prepared to make, has increased as a result.<sup>33</sup> In the delivery and operational phase of an engineering project, due diligence helps to *protect* accumulated value by reducing operational risks (figure 7).

Here a word of caution is needed. Large engineering projects in particular have appalling success rates, as low as one in three, and some of the reasons are discussed below. One might ask why project owners and investors proceed given the high probability of failure, especially when specialist companies hired to evaluate the readiness of a major project give it a low chance of success. These specialists told us that owners exhibit a degree of over-confidence in making decisions to proceed with their projects. Owners tend to discount their advice and assume they can easily rectify any shortcomings they pointed out during the course of the project.

Is it possible that engineers are perhaps too successful in building investor confidence, resulting in over-optimistic expectations? Kahneman and Lovallo demonstrated how organizational optimism arising from attachment to a specific project contributes to high the high failure rate experienced with major engineering projects.<sup>34</sup>

#### Inspection, testing and design checking (6)

Our research has shown that engineers devote as much attention to these performances as creating the design and analysis results.<sup>35</sup> However, investor expectations are influenced more by perceptions than actual engineers' performances. Formal quality assurance systems, often with external auditing, are therefore critical in creating the perception by investors that checking, testing and inspection is sufficiently rigorous to reduce *perceived* risks.

Even though this is a large aspect of engineering work, as explained in section 9 a few pages further on, engineers systematically relegate,<sup>36</sup> defer, or even skip significant parts of design checking and inspection work. We discuss this issue in section 9.

#### Project and design reviews (7)

As explained in section 2.2, in the early stages of an engineering project, engineers conduct feasibility and design studies to reassure investors that the technical and commercial risks are acceptable, and are sufficiently low to commit the funds and other resources needed to implement the project. A final investment decision (FID) to proceed with a large project depends on creating a high enough level of trust and confidence. In reality, any large engineering project will require successively more detailed feasibility studies and project reviews leading to investment decision 'gates'.<sup>37</sup> At each decision gate, investors need to be satisfied that committing further funding will sufficiently reduce uncertainty in project outcomes. The final investment decision typically requires about 90% of the total project expenditure to be committed, and there is usually no way to recover that expenditure afterwards if the wrong decision is made.

A common practice in large projects is for the project owners to commission external reviews by experts who examine engineers' documentation describing project plans and designs. Often the reviews will recommend that engineers consider additional factors and perform additional work to check the accuracy of earlier

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<sup>33</sup> (see also Trevelyan & Williams, 2018b)

<sup>34</sup> (Kahneman & Lovallo, 1993). Daniel Kahneman is well known for his popular book in which he explains flaws and biases in human decision making (Kahneman, 2011).

<sup>35</sup> (Trevelyan, 2007, 2008)

<sup>36</sup> Meaning to assign an inferior value

<sup>37</sup> (Phillips, Neailey, & Broughton, 1999; Trevelyan, 2014, Ch11)

predictions. These checks are in addition to internal reviews and formal document checking required for quality assurance.

### Compliance with standards (8)

Another way that engineers reduce uncertainty is through compliance with technical standards. Technical standards provide engineers with guidance, helping them arrive at error-free solutions more quickly.<sup>38</sup> Educating investors about reducing downside risks through compliance with relevant standards may be necessary, of course, to influence their perceptions.

*Practice Question: Given the background in this guide, explain how stage gate decision making processes in engineering projects help to build investor confidence. A project passes a series of decision gates before the final investment decision. At each decision gate, additional funding is allocated for engineering work leading to the following decision gate. Explain how increasing investor confidence is related to the increased funding provided for the project and how this changes the exchange-value attributed to the project by investors.*

*For a detailed explanation refer to Trevelyan, J. P. (2014) “The Making of an Expert Engineer, Chapter 11, pp 399-410. Read this chapter (or another reference text on the subject) before writing a concise summary.*

*Practice Question: Find industry position papers that discuss design reviews, particularly design, operability and maintainability reviews, typically in the context of lessons learned from major engineering projects.*

## **5.2 Value delivery from technical collaboration**

This section is necessarily more extensive since a formal understanding of technical collaboration is relatively new in engineering practice.<sup>39</sup>

### Reliable technical coordination (9)

Engineers spend much of their time negotiating and coordinating technical work performed by others.<sup>40</sup> Much of this is informal and undocumented. Project management is the same performance formalised and documented which is essential when the work scope is too great for normal human memory. Such coordination serves to maintain the integrity of technical intentions, in other words to align collective actions by many different people with designed technical intentions so that the desired technical (and commercial) performance is achieved in the end.

Engineers enact a complex series of what Trevelyan has termed ‘technical collaboration performances’<sup>41</sup> that form multiple layers of defence with the aim of implementing the original technical intentions sufficiently well to obtain the expected level of performance, both technical and commercial.

In reality, however, there are large uncertainties in delivering contemporary engineering projects, particularly projects over USD 1 billion where success rates are only about 1 in 3, even where the success criterion is based on investors receiving only half their expected return on investment.<sup>42</sup>

To understand the kinds of uncertainty that affect technical collaboration, we will explain just two or many aspects: creating project design and planning documents and interpreting them.

Consider designs represented by drawings or CAD models. Almost always these define attributes of the end product, the final artefact, and reveal relatively little about how to create it. The design is often a simplification of reality in many respects. The knowledge of actually building and maintaining artefacts relies extensively on unwritten tacit and implicit knowledge carried in the minds of the people involved, and this knowledge is critical for appropriate interpretation of plans and drawings.<sup>43</sup>

<sup>38</sup> (Trevelyan, 2014, p. Ch 3)

<sup>39</sup> See (Trevelyan, 2014, Ch7-12)

<sup>40</sup> (Trevelyan, 2007)

<sup>41</sup> (Trevelyan, 2014, Ch7)

<sup>42</sup> The data come from commercial organizations hired by investors to forecast the likely success of large engineering and infrastructure projects at the investment stage (Flyvbjerg, 2014; Merrow, 2011). Routine building construction projects have better success rates. Similar issues affect small projects to varying extents, sufficiently to raise concern among clients and engineers’ employers.

<sup>43</sup> (Bea, 2000; Trevelyan, 2014, Ch5)

As an illustrative example, diagrams illustrating complex electronic circuits comprising integrated circuit chips rarely show the power and ground connections: these are omitted for clarity. Including them would add visual complexity making the circuit diagrams harder to understand. These connections are implied, and often not explicitly specified at the design stage.

Because human interpretation is critical, and no two interpretations are identical, engineers find themselves constantly resolving ambiguities and differences of interpretation, and are often forced to make difficult decisions on compromises with uncertain technical implications. Here is an example from our data:

*“Our inspectors rejected a cable installation because the unsupported length of a section of electric power cable was longer than permitted in the relevant standard. However, the local engineers needed help to find an acceptable work-around so the project could comply with standards without unacceptably costly rework.”*

The physical installation of cables is rarely explicitly specified beyond the provision of cable trays in the structure. Normally, an electrical wiring standard will be specified, but this relies on knowledge of the standard among the construction workers which can be tenuous in cases (like this one) where the work was outsourced to a low wage environment in the belief that it could be completed at less cost. When the cost of supervision and reworking is taken into account, apparent labour cost savings have often turned out to be false expectations.

Technical foresight and planning is another complex engineering performance.<sup>44</sup> Engineers transform a design that shows only the essence of the completed artefact into a detailed, comprehensive set of plans and instructions to identify, procure, transport and store all the materials and components and then safely and reliably transform them into the completed artefact with acceptable quality, operating reliability, longevity, environmental impact within the client's cost, time and resource limitations. The plans also have to detail the tools, facilities, finance and labour required, along with appropriate suppliers, contractors and service providers, ensuring that these resources will be available for the expected times they will be needed. This requires extensive tacit knowledge accumulated from experience, and engineers with different background knowledge, working practices and experience will provide quite different plans. In all but the smallest project, this requires more knowledge and experience than a single engineer can reasonably provide, so it has to be a collaborative effort using distributed expertise and coordination.<sup>45</sup> Consequently, much of the effort is spent reconciling and successfully integrating plans produced by different engineers with different experience and understandings of the project requirements.

Meticulously detailed planning information compiled in project planning documents,<sup>46</sup> one might assume, should ensure that project work is well coordinated. However, the project work is seldom coordinated by the same engineers who compiled the planning documents. A new cadre of engineers have to appropriate<sup>47</sup> this information because human decisions are based not on written information, but knowledge (true justified beliefs) in the minds of project participants.<sup>48</sup> Yet project management texts pay relatively little attention to the challenges of ensuring that everyone appropriates sufficient information to make the best possible decisions. Engineers make countless instinctive trade-off decisions every day, deciding for example, which issues need further investigation and which can be safely deferred, perhaps never to be attended to. They can receive several hundred emails a day, and have to decide which can be ignored or quickly scanned. Some they will have to read in detail, but they cannot possibly read every email and absorb even a small proportion of the details.

We chose these two factors, creation of plans and documents, and the subsequent interpretation of them, from many other possible factors. Both factors illustrate how human differences (in interpretation and learning) will influence the results of engineering work on any project. Therefore, engineers must somehow overcome such interpretation and learning differences or else we would not see a significant number of successful projects.

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<sup>44</sup> (e.g. Winch & Kelsey, 2005)

<sup>45</sup> (Trevelyan, 2014, Ch5)

<sup>46</sup> Planning documents are specified in great detail by, for example, the Project Management Institute, which also offers accredited project management qualifications.

<sup>47</sup> Appropriate – the meaning here conveys a form of learning, rather than taking possession of an artefact.

<sup>48</sup> (Nonaka, 1994; Trevelyan, 2014, Ch5)

There are many techniques adopted by engineers to limit the effects of interpretation and learning differences. From carefully designed organisation procedures to technical standards, engineering firms have evolved working methods to constrain the effects of human interpretation differences. Engineers, therefore, bring specialised knowledge which turns out to be of critical importance in what might seem to be dull, boring, routine engineering work with little if any opportunity for technical innovation. By applying these methods, engineers deliver project outcomes that bring use-value to project sponsors: greater predictability of project outcomes (albeit still with significant variability) and hence less incidence of “nasty surprises”, unpredictable situations leading to substantial loss of economic exchange-value for investors’ assets.

Therefore, reliable technical collaboration not only creates value by reassuring investors *before* they make the final investment decision, but also helps to *deliver* the anticipated value, or *protect* the potential value represented by the investment decision (figure 6). A project that fails to deliver investors’ expectations not only destroys value, but also damages reputations for all involved.

How can we begin to quantify the value created in this way?

At the final investment decision (FID) one can argue that the exchange-value of a project is equivalent to the amount to be invested. However, given the relatively low chance that a large project will succeed as intended, we can also assert that the likely exchange-value of the project is less than the capital sums set aside by the investors at FID. The value should be discounted according to the probability of success. In the words of a merchant banker familiar with the success rate of major projects “We always discount engineers’ predictions: if they say the rate of return is 20% we will mentally adjust and plan on half that or less.”

Therefore, in the event of a successful project of this kind, one which fulfils investors’ expectations at FID, the exchange-value of the project has been increased by the inverse of the banker’s instinctive rate of return discount reported above. With an overall success rate of 33% for large projects, we could argue that the increase in value resulting from successful project delivery could be as much as two thirds of the total investment. Yet, the engineers involved have not contributed to the design (except where needed to rectify errors or omissions left after the FEED<sup>49</sup> team have finished their work), and their work has almost entirely been routine and not innovative. In other words, engineers are creating value in ways not anticipated by the current business value creation literature that focuses entirely on technological innovation. Even if one were to argue that the project value at FID is the sum invested by the project owners, then successful project delivery represents successful *protection* of the original value at FID. Not all projects are successfully delivered so, according to this view, engineers are not always successful in *protecting* the project value created by the FEED activity prior to FID.

### Teaching, building skills (10)

Engineers spend extensive time on both formal and informal teaching in the workplace.<sup>50</sup> Most of the risks associated with engineering projects are associated with differences in human perceptions, understandings, interpretations and resulting behaviour (Trevelyan, 2014, p. Ch 10). Education and training help to reduce the downside risks associated with human factors (Bea, 2000; Busby & Strutt, 2001) and hence, by similar arguments presented above, to add value. A key factor in many investment decisions is the perceived level of technical skill in the enterprise, and the ability to maintain sufficient skill levels through the life of the enterprise.

In some contexts, engineers speak of “A-teams, B-teams and C-teams”. A-teams are highly trained and experienced and are known for their ability to reliably deliver intended results on time, given appropriate resources. B- and C-teams deliver results, but require more supervision effort, training and possibly more resources as well. Naturally, every project manager would prefer to have A-teams, but the reality of engineering projects is that A-teams are often already committed to other projects. Often it is project delays that lead to non-availability of the preferred A-team. Engineering supervision of B- and C-teams is, in essence, a teaching and skill-building performance.

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<sup>49</sup> FEED: front end engineering design, usually referring to engineering design performed in advance of the final investment decision.

<sup>50</sup> (e.g. Bailey & Barley, 2010)

### Social licence to operate: co-creating value with communities (11)

A comparatively recent development in engineering practice (since the 1980s) has been the introduction of comprehensive health safety and environmental monitoring practices.<sup>51</sup> Public concerns following major disasters led to complex industry regulations, these practices have also been motivated by changing performance expectations among engineers as well.

Many engineers find it hard to understand how these practices add value: most see government regulation as a costly additional burden on engineering projects.

In essence, these engineers are creating and maintaining a “social licence to operate” without which a company will either encounter significant regulatory obstacles or worse, face the prospect of being closed down in response to what may be ill-informed community protests.<sup>52</sup> Engineers working on health, safety and environmental management systems, therefore, can be seen to be enacting value creation performances, even from a narrow enterprise-based perspective.

Decreasing the risk of major project delays or premature closure on environmental or social impact grounds results in increased project value for investors, following the same arguments presented earlier.

Recent discussions on value creation and corporate social responsibility has led to the notion of value co-creation in communities. Porter and Kramer show how enterprises can create value both within themselves and the communities in which they operate with appropriate activities.<sup>53</sup> They argue that long-term success for an enterprise depends as much on developing the community that hosts it as on commercial performance. In making this argument, they have opened up further opportunities for engineers to contribute to value creation through practices that have been frequently associated with sustainability or corporate social responsibility.

Well-established practices such as building community respect and a social licence to operate, as well as co-creation of community value motivated by a more far-sighted attitude to enterprise success from a corporate social responsibility perspective can help resolve apparent conflicts between community and business interests. Many experienced engineers understand value is created by taking time to consult with regulatory authorities informally to build their trust and confidence in an engineering project team. Regulators, consequently, are less likely to demand intrusive inspections and audits that can be extremely arduous and time-consuming for engineers working on these projects.

## **6 How do engineers protect value?**

### ***6.1 Sustainment: operations, asset management and maintenance (12)***

Engineering operations, engineering asset management, and maintenance engineering (collectively known as sustainment) are critical for *protecting* value embodied in engineered products, systems and business processes. These require elaborate technical coordination and other collaboration performances by engineers. For example, a gas pipeline needs carefully planned and implemented inspections and maintenance. Without these measures, the condition of the pipeline can deteriorate, resulting in considerable value destruction. Energy, water, transport, communication and sanitation services are critical for the functioning of all human societies: inadvertent failure can lead to enormous value destruction, disease and deaths, far beyond the replacement value of the engineered systems themselves.

Accountants use a fixed rate of depreciation as a crude measure of value loss but the rate of depreciation used for accounting purposes is often unrelated to the actual loss of value that depends on how maintenance is actually performed. This is seldom represented adequately by recorded data.<sup>54</sup> For example, an accountant may wish to maximize losses early in the life of a productive asset in order to take advantage of certain taxation rules. A very different strategy is needed to maximize value protection for the physical asset.

Engineers engaged in operations and maintenance, by the same argument explained above, can also be said to be engaged in *value protection* activity, maintaining an enterprise in a state in which it delivers profits for its

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<sup>51</sup> Usually referred to as HSE practices.

<sup>52</sup> (Hardisty, 2010; Trevelyan, 2014, Ch12)

<sup>53</sup> (Porter & Kramer, 2011). This work represents a considerable change from Porter’s original 1985 explanations on value creation.

<sup>54</sup> (Gouws, 2014; Nair & Trevelyan, 2008)

owners in line with the original predictions.<sup>55</sup> According to recent research, even well-managed engineering enterprises are suffering opportunity costs equivalent to 30-50% of turnover due to maintenance and operating mistakes.<sup>56</sup> Maintenance is a complex socio-technical activity that is not well researched or understood and improvement efforts by many well-informed organizations have yielded disappointing results, partly due to lack of understanding of these sociological factors.<sup>57</sup> For example, a common deficiency in maintenance coordination systems adopted by companies is to record and reward only the performance of maintenance tasks, rather than the quality with which the maintenance task is performed. As in the case of large engineering projects, we can argue that value protection activity by engineers is not guaranteed and it would appear that there could be significant opportunities for improvements with appropriate research-based knowledge (which does not yet appear to be available).

## 6.2 *Environmental protection* (13)

Engineers protect naturally endowed value by conserving the renewable and non-renewable resources of our planet, our home and by minimizing other environmental impacts. These performances also protect value represented by a [social licence to operate](#). The arguments presented above in the section on reliable technical collaboration show how decreasing the risk of major project delays or premature closure on environmental or social impact grounds results in increased project value for investors.

## 6.3 *Defence and security* (14)

Engineers provide many products and services that limit or prevent destructive behaviour by other people, thus protecting accumulated value represented by our society and its various cultures and civilisations. Value is created even if a conflict never occurs. First defence systems have deterrent value, reducing the likelihood of destruction caused by actual conflict. Second, good defence equipment limits destructive behaviour and reduces the extent of destruction sustained. Finally, use-value can be perceived as “a feeling of security” or “peace of mind” similar to an insurance policy.

## 7 *Advocating for sustainability and climate action*

Many engineers find themselves in conflicted situations where clients demand least cost solutions with the minimum possible compliance with environmental regulations and sustainability principles. The principles explained in section 6 can help engineers mount powerful arguments to persuade clients and even government agencies to be more proactive in facing sustainability issues and climate action. For young engineers who have a different perspective on the future from their seniors, the capacity to influence financial decisions can help them move from a potential conflict of values into a productive and value-generating solution space.

The financial imperative influencing many engineering clients is the cost of capital for investment. For example, constructing a mineral processing plant in a country with unstable politics requires investors with an appetite for high-risk ventures. Almost invariably, the cost of capital will be high, perhaps 15% to 25% above prevailing bank interest rates. In terms of NPV analysis, that means that future benefits are less significant than short term costs. Engineers will be asked to find solutions with the least up-front costs, with minimal allowance for meeting environmental standards. Almost certainly in these settings, there will be further cost penalties for providing security and facilitation fees for local public and private agencies that will help keep powerful political actors on-side.

One of the most significant ways that engineers can help generate value in these situations is to help firms lower the cost of capital. Compliance with standards such as [The Equator Principles](#) can unlock lower interest funding from banks and venture capital firms that value their reputations in wealthy countries. There are many examples of projects where major banks and finance companies have either declined capital [or have withdrawn their funding](#) for projects that are considered to be incompatible with sustainable business practices. Major banks regularly face pressure from shareholders and customers arising from the actions of domestic environmental and social action groups opposing projects which are often located in other countries. In Australia, for example, it is now considered risky for major financial institutions to provide capital for fossil fuel projects, particularly coal mining ventures.

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<sup>55</sup> (Orr, 1996)

<sup>56</sup> (Hägerby & Johansson, 2002)

<sup>57</sup> (Gouws, 2014; Gouws & Gouws, 2006; Gouws & Trevelyan, 2006; Nair & Trevelyan, 2008)



Another way for engineers to advocate for proactive action on sustainability and climate action is to raise the possibility of future regulatory changes, changes which may be retrospective. Political instability is often heightened by external economic pressures on a local economy that local political actors may be powerless to prevent. For example, local food price rises may be caused by global shortages or, as is presently the case, armed conflict in Ukraine, a major supplier of cereal grains and wheat. Politicians may seek scapegoats, enterprises that may be arbitrarily shut down or restricted simply because a government needs to be seen to be taking action, even though that action may not change anything.

Companies that are proactive on sustainability issues and also invest in the local community will be able to build a more robust reputation, or [social licence to operate](#). Many companies operating from wealthy countries will face much tougher expectations to maintain their social licence to operate, almost entirely because of domestic pressure. However, this also means that the firm will be less likely to face arbitrary closure or restrictions in a more politically unstable country.

Regulatory changes may be accelerated by political responses to climate changes or simply a longer than usual run of bad weather. For example, engineers at an Australian brewery argued for many years to recycle process water that would otherwise be discharged with biologically active contaminants, albeit within local regulatory limits. They struggled to demonstrate sufficiently positive NPV to secure approval for investment finance. A sympathetic accountant within the firm eventually managed to help them adjust the figures so the NPV was just high enough to justify the investment decision. Shortly after the water recycling plant started operating, the state government declared a drought after a year of minimal rainfall. The plant's water supply was severely restricted. With the recycling plant operating, there was just enough water to keep the plant running. However, the firm's competitors had to close their local breweries, forcing them to import beer from other plants hundreds of kilometres away, so the firm made much greater profits as a result of restricted supplies from competitors.

Engineers can bring this kind of foresight to the attention of decision-makers. If engineers can frame their arguments in terms of value generation principles – value creation, delivery and protection – financial decision-makers are more likely to take engineers' arguments into account.

## 8 Opportunities and Roadblocks

Engineers who master the concepts in these pages may still encounter significant barriers when they try and apply the principles of value generation in engineering practice.

### 8.1 Value engineering?

In many engineering projects, the client firm employs engineers who issue tender documents, specifications and design drawings. A contractor may find little appetite for value-generating ideas such as adjusting specifications and requirements documents to enable greater value generation. The traditional practice of value engineering, for example, normally requires a detailed analysis of every component to reduce costs. Options may include eliminating the component, combining its function with another component, changing the material specifications, simplifying the design or assembly operations.

We argue that value engineering should also include consideration of the client's needs to identify opportunities to provide greater value for the client through design changes, rather than merely reducing the cost of the individual components. For example, a low value component such as a sealing ring could be replaced with a more expensive equivalent to eliminate the chance of failure with negligible change in the overall cost.

One potential roadblock may be that the client's engineers issuing requirements or documents have little understanding on engineering value generation. Even today, six years after our theoretical ideas were published, the authors are not aware of any move to incorporate these ideas into engineering undergraduate textbooks. Therefore, the contractor engineers may need to help the client engineers understand a little more and argue more effectively for financial resources in their area.

For example, I recently helped asset management engineers in a major government utility to significantly increase their enterprise's maintenance budget. The engineers had, in part, based their maintenance budget requests on the published asset values in the utility's annual report. However, they were unaware that the asset values in the annual report were *depreciated* to represent fair value at the time. Using published benchmark

rates, I estimated that the asset replacement value was around 15 times greater than the published asset value. This helped to confirm that the maintenance budget needed a substantial increase.

## **8.2 Early collaboration opportunities**

The greatest opportunities to generate value for client firms come well before they call tenders for external contract work. By closely collaborating with a client through the early stages of a major engineering project, a contracting firm can often suggest major cost-saving measures and also place their own firm in the “box seat” to win the subsequent tenders for higher value work. At these times, it is still possible to influence the tender writing process to favour options that generate greater value for the client while also better matching the capabilities of the contracting firm.

For example, it is common practice for manufacturers or mining companies to specify a production plant with a certain “name-plate” capacity to match the firm’s average expected output. In practice, however, it is very difficult to ensure that all parts of the production plant can operate continuously at this capacity. Even if there are no bottlenecks, it often takes 2 – 3 years to ramp up production to full name-plate capacity. Typically there will be one or more bottlenecks that limit production capacity of the entire plant. Furthermore, with these production limits, it may never be possible to catch up on a given production schedule after unscheduled production interruptions or downtime.

The market price for the plant’s production will inevitably fluctuate. It is financially advantageous, therefore, to maximise production when prices are higher, improving the plant’s revenue by exceeding the name-plate capacity.

Finally, it is rare for a production plant to operate for a decade or more without the need for capacity improvements and other enhancements to adapt to changing market conditions. In many cases, it is far cheaper to build in excess production capacity at the start than to modify an existing plant many years later. For example, machines, material and components in plentiful supply during the original construction may be hard to procure just a few years later.

Therefore, by identifying commercial opportunities and likely production bottlenecks in advance, an engineering team can often argue for building in excess capacity on the basis of greater value generation. These design alterations can help ensure that plant production can exceed the name-plate level when needed.

## **8.3 Identifying client requirements**

Another opportunity for value generation lies in an accurate and detailed needs assessment for the client. Well organized contracting firms typically engage the client’s staff in extended meetings and design reviews to ascertain the client’s actual needs. Many clients lack the technical capacity and understanding to identify their own needs without expert assistance. If this step is missed, the client may be very disappointed with the results when a contract is completed, simply because of incorrect assumptions defining the client’s needs at the start.

It is wise to adopt a systematic approach to needs assessment which can take many weeks or months. Often it can be difficult to persuade client engineers to engage in protracted meetings that seem to take hours to resolve apparently insignificant details. However, an experienced contracting firm will know which details have to be clearly defined at the start to avoid disappointment later when the cost of rectifying issues is much greater. In fact, systematic need identification procedures often distinguish firms that can compete successfully with high hourly rates for their engineering work.

In an interview with a senior engineer responsible for several large mineral processing plants, he explained that nearly a billion dollars had been wasted in a series of capacity-building projects in the previous year. The contractors had provided improvements that were fully compliant with the client’s specification documents. However, the improvements provided no additional value for the client. In every instance, the contractors had provided detailed design documentation and offered on-site meetings to work through all the documentation in advance with the client’s engineers. However, the client’s engineers, designated as production superintendents rather than engineers, had failed to attend these meetings saying they were too busy with pressing production issues that had to be sorted out. The contractors, of course, could not force the client engineers to attend these meetings. The contractors made money, but the client was left with machinery and plant that did not add significant value.

A further value generation opportunity lies in bringing clients face-to-face with equipment suppliers. Peter Meurs helped the Fortescue Metals Group commission their iron ore processing facilities in the early 2000s at about two thirds the expected cost and several months early. He took the project owners on an international tour to meet the expert designers at major equipment vendors. Through these meetings, the vendors were able to identify alternative equipment configurations that were less expensive, more readily available, and more productive than the ones specified by the original project design team working far away in Perth, Western Australia. Naturally, Peter Meurs had to mount a strong argument for high level executives to take time out to go on such a tour at considerable expense. However, the results amply justified that decision.

#### **8.4 Public sector constraints**

Government engineering enterprises, particularly in lower-income countries, can pose significant roadblocks as normal concepts of commercial value can be difficult to translate into a public service utility setting. For example, a waste management utility in Pakistan struggled to achieve better than 90% availability for their fleet of vehicles because of a chronic shortage of cash to purchase good quality spare parts. However, when the maintenance engineers realised that the vehicle fleet could also service the needs of private firms with special waste disposal needs, the utility was able to raise additional finance outside their government operating budget. This provided sufficient income to overcome shortages of spare parts, helping to significantly improve the availability of their operating vehicle fleet.

#### **8.5 Adding value through marketing**

Contracting and consulting firms require significant resources to work with clients outside of funded project work. For that reason, small consulting firms will allocate as much as 40% of revenue towards marketing and business development activity with the knowledge that a large proportion of value generation work takes place outside normal project work. Obviously, they need to charge higher hourly rates to recover this expense. However, client firms will be more satisfied and willing to pay more, knowing that they will obtain a better result overall.

Many of these topics are explored in greater detail in “The Making of an Expert Engineer” by the first author.

## **9 Major Research Findings**

### **9.1 The link between engineering and business: why firms employ engineers**

Understanding engineering value creation, delivery and protection, particularly economic value, helps explain why firms, governments, and clients employ engineers.

Even though many engineers gain great satisfaction from seeing abstract ideas emerge into reality, few engineers could do that without being paid, and that requires enormous investments by project owners.

Therefore, understanding value creation helps explain the main reason most engineers do engineering: to earn a reasonable living. This understanding could help engineers find work with small firms, some of which may never have employed an engineer before.<sup>58</sup> Some of the engineering employers and politicians expressed great frustration in research interviews because, as they see it, engineers today have little understanding on how their work contributes commercial and even social value. The research we performed helps to demonstrate that their perceptions are often very accurate. We expect that students who study this guide will join a growing number of engineers who do understand how their work contributes value.

The marginal revenue productivity theory of wages explains how engineers who create more value are likely to earn higher remuneration. Improving engineers’ understanding on value creation could help them add more value in future, and hence earn higher remuneration or other benefits.

A word of caution is necessary here. Value creation is not necessarily associated with value capture. Capturing (or appropriating) a reasonable proportion of value added requires a sound business model.<sup>59</sup>

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<sup>58</sup> (Trevelyan, 2014, Ch 1)

<sup>59</sup> (Teece, 2010)

## 9.2 *Autonomy, tacit decision-making, and engineers' remuneration*

Analysis of our data has also shown that engineers have a large degree of autonomy in their work. Apart from organizational processes and occasional requests from managers, most engineers were largely free to decide what they do and when on any particular day. Many engineers told us, however, that they experienced frequent interruptions resulting in fragmented attention to what they saw as core technical tasks, also reported by others.<sup>60</sup>

In this context, expectancy value theory predicts that engineers' priorities will reflect their internal subjective understandings of value.<sup>61</sup> In countless instinctive tacit decisions each day, for example in choosing which email to open next, engineers will make choices that reflect their subjective understanding of value. These decisions often involve implied or explicit value trade-offs. For example, observations have shown that engineers relegate, defer or even skip checking and review work because they think that design and calculation work is more productive while checking consumes time and money.<sup>62</sup> Even in major projects with strict, fully audited quality assurance and checking processes we found that engineers routinely skipped checking work, *even though they signed documents to certify that the checking had been performed*. This behaviour was so consistent between projects and firms that one has to conclude that there is a systematic effect influencing people who, nevertheless, are trying their best to be conscientious engineers.<sup>63</sup>

We concluded that the absence of a systematic understanding of value creation, delivery and protection in engineering work that allows engineers to develop the misleading perception that checking work diverts them from what they see as "more productive work". Engineers who understand how due-diligence creates value might be more inclined to prioritize routine checking and inspection work.

Our research has uncovered strong evidence that more attention to routine checking and inspection work can significantly improve the chances of success for large engineering projects.

## 9.3 *Ordinary routine engineering creates value*

Another significant finding from this research is that ordinary routine engineering performances create and protect value, even without any significant innovation. Given that engineering employment in R&D and innovation represents only a small proportion of the total, one can deduce that far more value is created in ordinary, routine engineering performances.

The quote in section 5 concerning clients who forgot to ask if something has been done before illustrates the deeply held belief by engineers that their work is only interesting when they are doing something new or solving challenging engineering problems.

While many engineering students see themselves as problem solvers, our evidence supports earlier research suggesting that technically challenging problem solving is relatively rare, and often the best solution is to find someone else who has already solved it before.<sup>64</sup>

Problem avoidance through the application of standards and known solutions is far more common.

Engineering due diligence (section 5.1 above) aims to avoid problems, particularly by thorough checking for compliance with standards.

In other words, good engineering is all about *avoiding* problems: an unsolved technical problem suggests a prior failure to anticipate and avoid it.

Here is a deep misalignment between the expectation created by education educators that engineers need to solve technically challenging problems and engineers' experiences of ordinary routine engineering. As a result, engineers see their routine work as relatively boring and uninteresting, and this misunderstanding can undermine many engineers' self-esteem. For example, after an interview with an engineer when some preliminary findings on technical coordination were discussed (Trevelyan, 2007) the engineer went on to say:

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<sup>60</sup> (e.g. Perlow, 1999)

<sup>61</sup> (Eccles, 2005)

<sup>62</sup> (Mehravari, 2007; Trevelyan, 2010)

<sup>63</sup> Several of the research studies remain confidential at the request of the sponsoring firms.

<sup>64</sup> (Jonassen, Strobel, & Lee, 2006; Korte, Brunhaver, & Zehr, 2018; Korte, Sheppard, & Jordan, 2008)

*“You know, now I feel so relieved that I am not the only engineer that hardly ever seems to do any technical work, real engineering. You have made me feel so much better about my job. I was beginning to wonder if I would ever find a satisfying engineering job here.”*

We think that engineering students can gain more satisfaction from their careers if they understand how ordinary routine engineering creates value.

For example, maintenance and asset management is often seen by engineers today to be low-status and boring work because they never design or build anything. That is also a misleading and incorrect perception because maintenance engineers often take on challenging design work to develop ways to maintain equipment where designers overlooked the need for maintenance.

Maintenance is often regarded by enterprise owners as merely a “cost centre” where expenses can be trimmed without immediate consequences.

However, by understanding maintenance in terms of value protection, engineers are better equipped to help owners understand its importance, in a way equivalent to taking out insurance. Good maintenance protects accumulated value and provides owners with ‘peace of mind’, use-value, like an insurance policy, from the knowledge that it helps to avoid breakdowns and service interruptions at the worst possible times.

## 10 Guidance for Educators

Broadly speaking, there are three opportunities for educators to help ensure that engineers can understand how their work generates value.

1. Undergraduate education: engineering faculty can work with students, for example, framing questions in ways that help them appreciate the value of engineering analysis capabilities that form the major part of an undergraduate engineering curriculum.
2. Workplace education: supervisors and mentors can work with early- and mid-career engineers to help them understand how value is generated from their work, and how to influence financial decisions using concepts and language that are meaningful for decision-makers.
3. Many engineers liaise with engineers in their own firms and also the client organizations that commission their work. These engineers respond to financial decisions and, when asked for the rationale, will respond with something like “that’s above my paygrade”. It is likely, for the time being, that they also struggle to articulate how engineering activities generate value within their own firms. Therefore, it is likely engineers with the knowledge in this document will find themselves explaining value generation concepts to their peers and engineers in other firms. Doing so will help reinforce that understanding in their own minds.

### 10.1 A challenge for educators

The research findings explain why this topic is so important: understanding value creation, delivery and protection is fundamental for students and engineers to be able to explain the value of being an engineer.

Engineers should be able to explain the value of engineering in different contexts, especially how value is created in performing ordinary routine engineering.

If engineers are to be able to influence business decisions, it is surely important that engineers understand value creation, the fundamental factor that motivates firms to invest in engineering. Only with this understanding can they seek to convey their ideas in a language that makes sense in corporate boardrooms.<sup>65</sup>

It is tempting for engineering faculty to assume that one can learn this in business courses that might be options, or part of a combined engineering/commerce degree structure, or a postgraduate MBA program. However, our research provides significant evidence that engineering graduates with business degrees were no more able to explain how their work generated commercial value than students with no business studies in their courses.<sup>66</sup> Why? The reason seems to be that there has been no theory to explain how engineering activities generate commercial value other than innovation, research and development. Hence the widespread advocacy for students to take entrepreneurship courses or options. As explained earlier, however, most engineers are not involved with the innovation ecosystem – startups, innovation companies, or government and major corporate R&D.

This document builds on the theory we found was missing: a rigorous explanation on how routine, everyday engineering generates commercial and social value. Without such a theory it is not possible for either business schools or engineering faculty to explain the links between engineering and business.

We do not advocate new courses or even a new course structure to teach this theory. Instead we argue that it is better to integrate an understanding of *value creation, delivery and protection* into existing courses across all engineering programs, from first year to final year. We offer suggestions on how this could be done in the following sections.

There are no specific skills to learn. Instead one needs to learn the context and purpose of what engineers do. For that reason we advocate framing learning exercises in different engineering practice contexts so that, gradually, students will come to understand the purpose of the work they will perform as engineers.

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<sup>65</sup> Interestingly, some academics continue to argue that engineering and business interests are fundamentally opposed (e.g. Conlon, 2018). We disagree, and argue that nearly all engineering depends on government or business investment and both kinds of investors are seeking to create value.

<sup>66</sup> (Crossley, 2011; Singh, 2015)

## **10.2 Encouraging collaboration**

We will raise one critical aspect of engineering value creation that needs a more radical rethinking of course design and assessment: technical collaboration (performance 9). Current education assessment and grading practices reinforce a culture of individual performance, year after year. In other words, it is only one's own performance that matters. Any attempt to grade a student or course participant on their ability to influence the performances of others by collaborating will be deeply resisted at an emotional level. Doing so conflicts with this formal education culture that has been reinforced for perhaps 15 years by the time students reach the final year of their undergraduate engineering course.

Educators, therefore, need to be aware of the possibility of deep-seated aversion to collaboration, particularly in an education setting. Even in the workplace, evidence from studies of early-career engineers demonstrates resistance to the social interactions critical for effective trust-building and collaboration.<sup>67</sup> Shery Turkle has also written about the aversion many young people develop through using text messaging as a seemingly safer substitute for direct face-to-face or telephone interactions with people, little realizing that this itself can be a delusion.<sup>68</sup>

Therefore, encouraging real collaboration between engineers can be difficult in higher education settings, and may require constant encouragement and monitoring in workplaces. For more see section 11.1.

## **10.3 Explaining the links between engineering and business**

Contemporary engineering students learn about links between engineering and business in several different ways.

Many engineering degree programs incorporate a business-related component as part of a standard degree. Typically this is a single semester course on engineering economics and finance. The course introduces accounting principles; relationships between cost, volume, and profit; discounted cash flow and net present value calculation; capital budgeting; and fundamentals of markets and prices.

Students may also learn project management, though most courses focus mainly on planning methods.

Entrepreneurship courses tend to emphasize smaller start-up firms and students typically learn about product innovation, intellectual property protection, creating a business plan, often based on case studies in local innovation firms.

These courses be modified so that students learn something about engineering value creation. However we think that a different approach is preferable.

Business-related courses are often taught by staff from a business school who have even less knowledge of engineering practice than engineering faculty. As Trevelyan and Williams have explained, the business literature cannot explain engineering value creation beyond technological innovations.<sup>69</sup> As the same time, it is unusual to find engineering faculty with substantial understanding of finance and economics. Current courses mostly leave it to students to figure out the conceptual links between business and engineering.

Many universities advise students to take a minor or second degree in commerce or economics, and many other engineers choose to study a postgraduate degree such as MBA.

## **10.4 We need a theory**

Theoretical understanding is critical for effective teaching.<sup>70</sup> Imagine teaching multiplication without the routine methods emerging from number theory: children would need to be taught every possible combination of two numbers and learn the resulting multiplied value by rote. Education research shows that the conceptual links between different ideas have to be made explicit to students for effective learning.<sup>71</sup> Therefore, a theoretical understanding of value creation in engineering is necessary for effective student learning.

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<sup>67</sup> (Leonardi, Jackson, & Diwan, 2009; Perlow, 1999; Trevelyan, 2019)

<sup>68</sup> (Turkle, 2005[1984], 2017)

<sup>69</sup> (Trevelyan & Williams, 2018a, 2018b)

<sup>70</sup> (Bransford, Brown, Cocking, Donovan, & Pellegrino, 2000)

<sup>71</sup> (Marton & Pang, 2006)

Trevelyan and Williams have demonstrated that the current literature and theories on value creation focus almost entirely on innovation and entrepreneurship.<sup>72</sup> Therefore, in the absence of an explanation on how other performances create value, engineers today learn to associate value creation only with innovation and challenging technical analysis. Our qualitative analysis has confirmed this.

Now it is possible to see why it would be hard for engineering educators today to teach engineering students about value creation. A coherent theory on engineering value creation is essential and has, until now, been missing. In our research publications and in this guide we have proposed the elements of such a theory so it is now more possible to teach students how value is created in routine everyday engineering.

One should be cautious in advocating curriculum changes as a means to influence practice because so little is known about causal links between education and practice.<sup>73</sup> Therefore, we have selected three examples of education contexts in which students could be helped to understand engineering value creation *without significant curriculum changes*. Given that most of the engineering curriculum consists of engineering science courses, we have suggested interventions that fit into these courses.

### 10.5 Learning how engineering analysis creates value

Most engineering courses today teach quantitative analysis methods. Students learn to apply mathematical approaches to calculate the technical performance attributes of man-made objects, sometimes natural objects as well. Figure 7 shows an example.

A 90 kg person, whose centre of gravity is located at point G, is standing on an inclined ladder. The horizontal distance from the bottom of the ladder to the person's centre of gravity is 2.5 m. The ladder is 5 m long and has a mass of 20 kg. You can neglect friction.

(a) Draw the free-body diagram of the ladder.

(b) Write the equilibrium equations for the ladder.

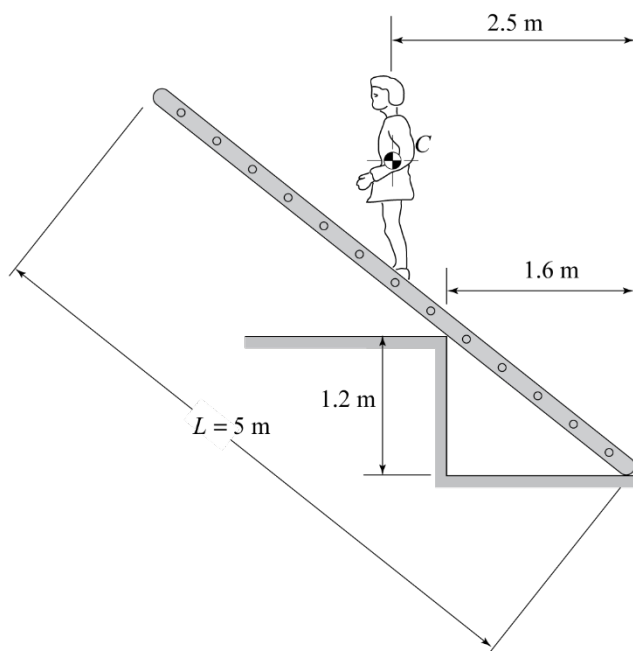


Figure 9: An engineering analysis problem

Students might be asked to determine whether the ladder is stable in this situation. In essence, students are being asked to forecast the behaviour of some man-made objects. They are practicing performance 5 – technical forecasting.

Slightly changing the problem description could help students understand that engineers need to allow for uncertainties and assess the likelihood of different and perhaps unexpected outcomes. The problem could ask students to assess the probability that the person will stand on different rungs of the ladder and then assess the risk that the ladder will become dislodged.

Students could be asked to estimate the performance margin of the ladder as shown: how much further up the ladder could the person safely stand? What design options are available to increase the performance margin?

<sup>72</sup> (Trevelyan & Williams, 2018a, 2018b)

<sup>73</sup> (Buch, 2015, 2016; Trevelyan, 2012, 2019)



Engineering analysis practice problems could easily be framed in terms of performance predictions for investors, reducing uncertainty, engineering due diligence, or even specifically a design review, like this:

*The drawing illustrates a circuit proposed for a phase locked loop frequency controller. The circuit components and other design details such as controller gain settings are specified in the diagram. Create a model of the frequency controller and analyse it to confirm that the controller gain will accommodate frequencies between 400 kHz and 250 Mhz. If the controller will not work as expected, suggest design changes that could readily be implemented.*

*(The circuit diagram and design details are not included here.)*

Students would perform their own analysis to determine whether the proposed design would work as expected. In doing so, they would not only learn more about phase locked loops and control system analysis, but also understand more about *the context* in which this kind of analysis might be conducted. The lecturer would be expected to explain to the students how investors are more likely to invest in an engineering project if the technical aspects have been independently reviewed by other engineers.

Practice problems for almost any engineering science subject could be equally framed in terms of other value creation performances. For example, a maintenance and obsolescence issue could be understood better through a problem that asks students to choose the most appropriate modern component to replace an obsolete component that has failed. The context could be enriched by providing students with information on the cost of the component, the likely delivery time, and the cost of a delay in restoring the system with the failed component.

Noting that, in practice, engineers require both quick (though approximate) analysis methods and more detailed and accurate methods, educators could require students to practice both, with the more accurate methods helping students understand the limitations of faster methods. Equally, students should be given problems with critical pieces of information missing. Students can be better prepared for practice if they learn ways to develop reasonably justified assumptions where information is missing. Equally, students should be able to estimate uncertainty in the final results, given uncertainties in the data.

For example, a typical scenario encountered in technical coordination (performance 9) is that some technical work has been performed incorrectly. An engineer needs to decide whether rework is needed. Either of the example problems shown above could be adapted to illustrate this scenario. For example, students would find that the height of the step on which the ladder is leaning in figure 9 is 1.5 m instead of 1.2 m as intended. Then they would be asked to find if this has affected the stability performance margin.

Finally, engineering students would benefit from being required to find missing logical steps, missing or mistaken assumptions, and mathematical or calculation errors in worked problem solutions. Engineering educators have ready access to examples from countless student submissions! Practice in checking written solutions in engineering coursework can help reinforce the idea that checking and review is part of real engineering work.

In order to make these changes in their courses, engineering faculty would need to learn about the different value creating, delivery and protection performances, and find ways to frame analysis problems in ways that illustrate these performances. Students would soon realize that they are learning about a much broader range of professional practice situations.

### **10.6 Routine practice problems**

Our analysis also helps to reinforce the need for engineering students to engage in extensive practice solving textbook mathematics and engineering science problems, even though they are unlikely to apply methods such as solving differential equations in their careers. Teaching maths to engineering students can be challenging because many students think (correctly) that they will never directly apply the methods they are forced to practice.

Goold and Devitt have shown how engineers routinely apply mathematics in a qualitative or tacit sense, without necessarily realizing it.<sup>74</sup> Our analysis shows that many engineers work on proposals, feasibility studies and commercial bids for projects that never eventuate. Most of the projects will not be ultimately

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<sup>74</sup> (Goold & Devitt, 2013)

approved, and typically between one in three and one in six commercial bids for projects are successful. These engineers have to estimate technical and economic performance often with extremely tight deadlines. Considerable value is created in doing so by identifying efficiency gains (2), product differentiation (3), analysis (4-5), due diligence (6-8) and reliable coordination (9-11) as described above: these performances help enterprises choose the best projects and the most appropriate and capable suppliers and contractors.

In these situations, engineers have to perform fast and approximate calculations: precise calculations usually take too much time. Choosing appropriate calculation methods that will provide quick results with a required level of accuracy is a critical skill and, as Goold & Devitt observed, demands qualitative and tacit understanding.<sup>75</sup> However, tacit knowledge can only be appropriated through extensive practice.<sup>76</sup>

By explaining how value is created in these ways, educators could motivate students to engage in extensive practice in mathematics and engineering analysis even though they are unlikely ever to need to apply those specific analysis methods for themselves.

### **10.7 Cost of employing engineers**

Understanding the cost of employing engineers is important when trying to argue that engineering activity will generate value for a firm. Also, it is helpful for engineers to be able to explain that the value generated from their work is significantly higher than the cost of employing them.

There is insufficient space in this article to fully explain these employment costs. However, it is safe to assume that the cost for most firms in wealthy countries will be about 2.5 – 3 times the salary paid to the engineer. In low-income countries, the need for costly supervision may significantly increase this multiple to 4 or more. This cost is primarily made up of the following components:

- Supervision time
- Cost of marketing to secure paid work for engineers to contribute towards
- Liability, health insurance
- Administration costs
- Access to databases and specialized software
- Office accommodation rent, power, water, parking, and other services
- Training
- Office equipment
- Special clothing, protective equipment for site work
- Taxes
- Superannuation or pension fund contributions
- Travel, working away from home allowances.

### **10.8 Case Study Suggestion – Safe Drinking Water**

We suggest that there is no better case study to illustrate value creation by design than drinking water supply: an essential role for engineers. The provision of piped drinking water has transformed human societies, perhaps more than any other engineering intervention. Water is heavy and carrying enough for a family can take hours of strenuous work. Asking students to carry the bare minimum for their family's daily consumption (10 litres per person not including toilet use) from a nearby source, say 1 km away, would be a memorable experience. Yet, even today, billions of people lack access to safe piped drinking water to their homes.<sup>77</sup>

Students could calculate the likely economic value contributed by piped water using a simple “value of time” measure: unpaid labour by family members is approximately equivalent to two-thirds of the average female earning rate in their community. Students could calculate the likely economic value added by a safe piped drinking water supply from measurements of their own carrying time.

At the most basic level, piped drinking water engineering requires little if any innovation and some of the simplest engineering components.

<sup>75</sup> (see also Gainsburg, 2006; Gainsburg, Rodriguez-Lluesma, & Bailey, 2010b)

<sup>76</sup> (Eraut, 2000; Polanyi, 1966; Trevelyan, 2014, Ch5)

<sup>77</sup> (e.g. Ahmad, Goldar, Misra, & Jakariya, 2003)

Students can then learn how choosing conventional technical solutions and applying engineering standards reassures investors who contribute the funding for major projects, whether from government or private sources. Here the emphasis is on reducing *perceived* risks, and hence increasing the *perceived* value of a project.

A water pipeline built 125 years ago provides an informative historical case study that demonstrates how the technical design of an innovative project can be manipulated to reduce apparent risks.<sup>78</sup> The chief engineer, C. Y. O'Connor, proposed a pipeline nearly 800 mm in diameter from near Perth, Western Australia to goldfields in parched desert 530 km away. Taken as a whole, the project was far beyond the state of the art at that time: till then, the longest water supply pipeline was 100 km and 250 mm in diameter. The new pipeline, 800 mm in diameter, would be constructed on the far side of the world from the industrial centres of the world at that time.

O'Connor's design consisted of a series of shorter 70 km pipelines, each pumping water to a modest storage reservoir feeding pumps at the start of the next section of pipeline. Each set of pumps was one tenth the capacity of the largest sand dredge at the time. With this design, he was able to argue that the project did not require any technology that had not already been commonly used elsewhere, reducing the perceived risks sufficiently for London-based investors to provide the funding required at a low interest rate.<sup>79</sup>

The cost of water at the goldfields was reduced by a factor of ten. Before the pipeline was built, water was produced in crude desalination plants from saline underground water. Once commissioned, there was ample affordable water resulting in dramatic health improvements and economic development of a huge region of Australia.

The project is also known for the death by suicide of O'Connor before the pipeline was completed.<sup>80</sup> Contributing factors were stress, extreme hot weather, government inquiries into corruption among project engineers whom O'Connor had trusted leading to sensational reports in news media, a new and unsupportive government administration and possibly liver disease. Thanks to many investigations and enquiries, we know more about O'Connor and his projects than many of his engineering contemporaries. These reports provide a rich source of learning for today's engineers.

This case study can readily be incorporated in courses on engineering design, sustainability, or basic fluid mechanics.

Water supplies are just one of many critical community services provided by engineers. Service learning is steadily gaining acceptance as an effective way to help students appreciate diverse ways in which engineers contribute social value. The EPICS program in the US provides many examples of such initiatives.<sup>81</sup>

## 10.9 Summary

We have proposed several ways in which engineering educators could help students to develop an understanding engineering value creation:

- i. Framing engineering analysis problems in ways that help students learn how engineering analysis can add value in an engineering enterprise.
- ii. Practice in solving routine mathematical practice problems enables engineers to make fast and approximate calculations to build confidence for investment in feasibility studies.
- iii. A case study suitable for a design or mechanics course showing how engineering safe drinking water supplies can contribute social and economic value, and how a design can be configured to reduce the apparent risk for investors in a project.
- iv. Learning effective technical collaboration and due diligence skills through engineering practice in virtual worlds that simulate real life engineering.

Students who understand value creation are more likely to enjoy a satisfying career with less frustration and higher earnings from more effective value creation performances.

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<sup>78</sup> (Evans, 2001; Trevelyan, 2014, Ch4)

<sup>79</sup> (O'Connor, 1896, p8:33). Available in electronic form on request from the first author.

<sup>80</sup> (Evans, 2001)

<sup>81</sup> (Lima, Oakes, & Gruender, 2013)

It will be easier for these students to explain how they will contribute to their societies in their careers, to answer the questions discussed in the opening paragraphs of this paper. They may even improve on our suggestion below (with our most important suggestions underlined):

*What is the value of engineering?*

*Engineers reliably conceive, deliver and sustain technologies meeting human needs, from safe drinking water to medical implants and mobile phones, creating confidence for people to invest sufficient resources.*

## 11 Guidance for Educators: Engineering Practice and Technical Collaboration

Section 8 above describes curriculum innovations that are relatively easy to implement in a conventional engineering degree course as they can be integrated into existing teaching practices.

As explained at the start of section 8, teaching engineering practice and technical collaboration requires a much more fundamental rethink. Nonetheless, we are hesitant in offering major prescriptions for change in this document. As we are both now retired, we will leave it to others to try out the ideas we are offering here. It will require engineering teaching faculty who are sufficiently courageous to fail and try several times again to get them right, but we think the potential rewards make these attempts worthwhile.

There are some significant difficulties to be overcome or bypassed.<sup>82</sup>

First, there are few engineering educators who have sufficient understanding of practice. Like other aspects of engineering, engineering practice teaching needs to be led by researchers who study engineering practice and currently only a handful of researchers are studying this topic.

Not only is there a lack of research-based understanding, there is also a critical lack of experience of practice in engineering schools. It might be helpful to contrast engineering with medicine. Practically all the teaching in medical schools beyond the halfway point in the curriculum is delivered by people who practice medicine every day in the wards of teaching hospitals. In contrast, few if any engineering educators have extensive experience of engineering practice beyond the confines of research laboratories.<sup>83</sup>

The easiest way to address this is, we suggest, to require students to observe engineers at work using prescribed field study guidelines. Students would be required to study all aspects of an engineer's work for a few days so they understand at least one context in which engineers perform their work.

Next, university performance incentives reward individual intellectual efforts: grades for students and publications for educators in leading research-based universities. In contrast, as we have seen through the research results, engineers work in an environment where success is determined not by our individual intellectual performances, but by the way our technical insights enable us to influence others to achieve consistent results that match expectations.

The practice of awarding grades for individual achievements over so many years creates a deeply embedded reluctance to collaborate and help others achieve success without necessarily gaining any immediate recognition. The effect is so often observed that it is often called "task-focus", a deeply embedded belief that a workplace challenge in the workplace can only be overcome by working harder *oneself*. If anything, collaboration in formal education is often seen as a form of cheating.

Our critics will point to team projects: class exercises assigned to student 'teams' where a common grade is awarded to the entire group, sometimes with an adjustment for individual performance. However, student team projects are almost always performed individually. At the start, students subdivide the work into what they see as manageable individual tasks. At the end, often in the early hours of the morning before the submission deadline, one or two members of the so-called 'team' will try and edit the individual contributions to make the team submission look like an integrated team effort, with varying degrees of success. As Sheppard and her colleagues have pointed out, few if any engineering schools specifically team teamwork

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<sup>82</sup> Based on (Trevelyan, 2014', Ch15).

<sup>83</sup> Cameron and his colleagues performed a detailed study in Australia (Cameron, Reidsema, & Hadgraft, 2011). Anecdotal evidence reveals a similar situation in both research-based and teaching-specialised engineering schools around the world.

practices, assuming that practice is sufficient for students to learn.<sup>84</sup> Unsupervised practice without feedback reinforces bad habits as much as good ones.

It is equally difficult to break away from the supremacy of the written word in formal education. Mass education that characterises universities today requires a focus on written forms of learning assessment that contrast sharply with the largely verbal culture and unwritten knowledge that characterises engineering practice. There are alternatives. Performances can be assessed, although such assessment can be more time-consuming. Tacit knowledge accumulation from laboratory experiences can be assessed using online testing instruments, the results of which predict abilities such as troubleshooting and fault diagnosis much better than conventional written assessments.<sup>85</sup> However, students remain with a deeply embedded notion that formal, explicit, written knowledge is more influential than verbal and tacit knowledge. Students emerge with another deeply embedded understanding that written knowledge and communication is superior to oral and tacit understanding and verbal communication through social interactions. In reality of course, the knowledge sharing on which all engineering practice critically depends requires trusting relationships that require extensive face to face interactions.<sup>86</sup>

While performance incentives in formal education remain misaligned with those that apply in engineering practice, any attempt to teach it will run into implicit contradictions between the collaborative practices students are trying to learn and how they are rewarded.

Finally, collaborative engineering practice would most likely comprise a relatively small and isolated component of a curriculum dominated by traditional engineering science studies. It might help to incorporate cooperative learning environments where social interactions are taught and practised. These techniques are known to be more effective than traditional learning.<sup>87</sup>

There is always a risk that students will show similar resistance to engineering practice studies as they do so often today with communication studies.<sup>88</sup>

We assert that students, therefore, will only engage in and learn real collaboration in circumstances where individual efforts cannot or are unlikely to succeed.

The following two subsections discuss approaches that we believe can be of value for educators aiming to close the gap between engineering practice and the formation of engineers.

### ***11.1 Practicing collaboration***

Open-ended industry-based capstone design projects, for example, have been implemented in many engineering programs as a way to promote real collaboration and they can be effective, especially if the project scope is so extensive that no one student could possibly achieve sufficient to pass in the time available. However, as has been noted before, students tend to subdivide the tasks into manageable individual performances requiring little or no collaboration. Further, open-ended projects pose significant assessment difficulties unless students themselves can learn to self-assess their work.<sup>89</sup>

Another way to require collaboration, we suggest, is to raise the quality expectation so high that practically every student will need help from fellow students to pass. Many if not most students develop an ability to judge the standard of work needed to achieve the desired grade level.<sup>90</sup> Many readily acknowledge that their work is not up to acceptable professional standards but instead represents a compromise on what they could provide if sufficient time were available. Few students realise that in real engineering workplaces they will constantly be short of time and always compromising on quality. There is never enough time for perfection. Further, professional engineers make mistakes just as easily as students.

In a professional environment, engineers receive support in the form of supervision, in-house and national standards, and libraries of similar work from past projects. Engineering firms have devised collaborative

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<sup>84</sup> (Sheppard, Macatangay, Colby, & Sullivan, 2009)

<sup>85</sup> (Razali & Trevelyan, 2012; Trevelyan, 2011)

<sup>86</sup> (Trevelyan, 2014, Ch5)

<sup>87</sup> (Smith, Sheppard, Johnson, & Johnson, 2005)

<sup>88</sup> (Emilsson & Lilje, 2008; Paretto, 2008)

<sup>89</sup> (Trevelyan, 2015)

<sup>90</sup> (Draper, 2009)

working methods that (usually) identify and eliminate serious mistakes and deficiencies. These include peer reviews using standard checklists, prototype testing, compliance checks with industry standards, and detailed inspections.

As they approach the end of their course, therefore, students could be required to complete limited scope exercises at a professional level of quality with, say, a 95% pass grade. To achieve this, students will need to collaborate and follow industry practices for checking and reviewing work to eliminate (as far as they can) any errors detectable to the graders.

### ***11.2 Learning from virtual worlds: simulating real world engineering.***

Bucciarelli proposed that engineering educators should turn to design-based open-ended instruction that would harness the power of online technology to approximate more closely the engineering workplace and with the rapidly increasing power of online technology.<sup>91</sup> This is an area that has been receiving increasingly more attention. Jonassen and colleagues have developed various online applications that simulate trouble-shooting and problem solving processes. Recent years have also seen a burgeoning of research into gaming and virtual worlds in training for a variety of professions including engineering.<sup>92</sup>

Collaborative gaming also offers opportunities to develop reliable technical collaboration and due diligence skills, particularly coordination and leadership skills (section 3.4) in an education setting rather than hoping that students will engage in sufficient extra-curricular activities to develop these skills.<sup>93</sup>

While the adaptation of extended reality technology, including virtual and augmented reality, has also begun to be explored to provide students with practical experience<sup>94</sup>, a review of the current literature suggests that there is still a gap in understanding how emerging technologies can be used to bridge theory to practice in engineering education<sup>95</sup>.

Such initiatives have also been receiving organizational support. Faculty at Coventry University collaborated on a Royal Academy of Engineering initiative with an industrial partner to develop engineering project management simulations in the Second Life virtual world<sup>96</sup>. At the same time, engineering cyber-environments like nanoHUB.org provide opportunities for employers and engineering faculty to collaborate in developing models and simulations which bridge processes of discovery with processes of learning.<sup>97</sup>

There has been a growing acceptance of modelling and simulation to expose students to routine engineering work. It is now feasible to provide students with learning environments that allow them to confront authentic ill-structured problems in an engineering workplace context. These can provide opportunities for students to learn and practice the performances that would help them create value for their future clients. Such simulations allow learners “to fail gracefully and develop an intuition for the underlying engineering artifact”.<sup>98</sup> Additionally they can be designed in such a way that they can be equally useful for in-company training or for undergraduate education and in this respect, the Royal Academy of Engineering initiative is significant in that the majority of the projects funded involved employer engagement with academics.<sup>99</sup>

### **Concluding remarks**

Finally, there is a large mismatch between the expectations created in the minds of students and the realities of engineering practice. Some of these have been mentioned in this guide but there are many others.<sup>100</sup>

Contemporary accreditation practices focus on outcome competencies: normally defined as knowledge, skills and attitudes. However, the focus on engineering education is almost entirely on knowledge, with much less attention given to skills and attitudes. In the absence of formal development through education, therefore, students emerge with unintended but nevertheless misleading expectations. In a sense, the deep resistance to

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<sup>91</sup> (Bucciarelli, 2003)

<sup>92</sup> (Hauge, Pourabdollahian, & Riedel, 2012; Rajan, Raju, & Sankar, 2013)

<sup>93</sup> (Knight & Novoselich, 2017; Salado, Morelock, & Lakeh, 2017; Trevelyan, 2007)

<sup>94</sup> (Ijaz, Marks, Hartley, Gibbens, & Thomas, 2017; McGovern, Moreira, & Luna-Nevarez, 2020)

<sup>95</sup> (Bairaktarova, Valentine, & Ghannam, 2023)

<sup>96</sup> (Harrison, Moore, Igarashi, & Somani, 2012, pp. 70-73)

<sup>97</sup> (Harrison et al., 2012, pp70-73; Madhavan & Lindsay, 2014, p647)

<sup>98</sup> (Madhavan & Lindsay, 2014, p647)

<sup>99</sup> (Harrison et al., 2012, pp70-73)

<sup>100</sup> (Trevelyan, 2014)

collaboration is an expectation that not explicitly articulated. Explicitly articulated expectations include the notion that the desirable elements of engineering work centred on challenging design and technical problem-solving, innovation and pushing the boundaries of technical possibilities. This explains why engineers see maintenance as boring, low status work because they think these desirable elements of practice are completely missing. An important challenge then for educators is to design learning environments that challenge and refine these expectations and thus produce future engineering professionals with the skillsets and attitudes they need to create value for enterprises and for themselves throughout their career.

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