

Understandings of Value in Engineering Practice

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Abstract— This paper draws on a large body of empirical data from interviews and field observations to suggest that many engineers, even some professional organizations, have difficulty explaining the commercial value of engineering work. This difficulty could contribute to a public and employer perception that marginalizes the significance of engineering work. Research data came from qualitative interviews with engineers in Australia and other material. Data from individual engineers and other studies contributes to a description that educators and engineers could draw on to better explain the value of engineering to students, firms and the community at large. This paper presents a limited sample of the evidence behind this research.

Keywords- *Engineering practice; engineering education; community perceptions of engineers*

I. WHY WOULD A FIRM EMPLOY AN ENGINEER?

What value can an engineer contribute? These are important questions, yet there are few if any useful answers in the literature of engineering education that would help engineering graduates respond quickly with a meaningful reply. The concept of value itself has many different meanings. Looking at economic benefits for different stakeholders is just one of many possible avenues to explore the value that can emerge from engineering.

Why is this discussion important?

First, it raises issues lying at the core of shared identity in the engineering community and the profession. Historical studies have shown how the value of engineering has been articulated at the societal level in terms of building the nation state, maintaining military strength, or advancing industrial competitiveness.[e.g. 1] However, this literature requires careful study for a reader to be able to explain the value of engineering in meaningful terms at the level of a single firm or small engineering enterprise.

Second, young professionals who can easily explain the relevance and value of their work in their community are much more likely to feel respected and valued. There are many indicators that expose continuing concerns among engineers at the relatively esteem in which they are held in comparison to other professions such as law and medicine. The lack of community understanding about engineering can be linked with the lack of discussion on this topic within the engineering community itself, and campaigns to reassert a public image for engineers. A large survey of ASCE members in 2006 revealed a widespread perception that they were undervalued, wanted more respect from the public, and more opportunities to lead project teams [2]. There have been calls for more public awareness in the several countries [3, 4].

Notwithstanding efforts across the professions to raise the profile of engineering, a brief survey of the public advocacy sections of ASCE, ASME, IEEE and EA web sites at the time of writing revealed neither a useful description of engineering nor its social or economic value. None described engineering work. Most emphasized creating new technologies, particularly IEEE and ASME who prominently displayed an iPad on its technology and society page. ASCE emphasized building water and power systems, for which a literal interpretation would be misleading because engineers seldom build anything themselves.

Third, research on engineering practice has revealed many instances in which engineers have had difficulties in understanding the relative priority of different aspects of their practice because they have limited understanding about the value created by their work. This leads to frustration, delays and added costs. The CEO of a large engineering enterprise expressed his frustration in these words:

"Our engineers don't understand the business imperative of this organization. They simply don't get it and it frustrates me immensely."

Similar frustrations from a different viewpoint have emerged from engineers in our research and other studies. Several have alluded to non-engineers in senior management with a limited understanding of engineering issues, for example

"This company is run by f---ing accountants! They just don't understand even the simplest ideas in engineering."

This study has revealed that while engineers have a solid understanding that their work contributes great value, this understanding is not easily articulated. Many engineers seem to have rather simplistic ideas about the economic value that their work creates, possibly placing them at a relative disadvantage in the contemporary post-industrial world of work. A recent US-based qualitative study revealed engineering students' notions of engineering in which economic considerations are not core to engineering as such, although they are key considerations in the working world [5].

The first half of the 20th century perhaps represented a golden era for engineers in the industrialized world. They were regarded as public heroes, providing great advances in material living standards. In the 21st century, engineering is taken for granted and has receded from the public eye. An ordinary person in the industrialized world today can switch on a light, turn a tap, or start a car without any concern that the electricity, water supply will not be functioning, or that the car won't start. The value of engineering, therefore, is much less apparent.

II. ENGINEERING VALUE IS MORE CONSPICUOUS WHEN IT IS ABSENT

The backstreets of South Asian cities provide an opportunity to appreciate the real significance and social value of effective engineering because it is conspicuously absent. We take good engineering for granted in Australia where potable water is piped 24 hours a day to kitchen and bathroom taps and usually costs less than US\$2 per tonne including connection charges. In most South Asian cities, water flows from pipes for an hour or so every other day and it is almost certainly unsafe to drink. Potable water has to be prepared or often carried by women, with the result that the real economic cost is many times higher than in Australia *in equivalent currency terms per ton*. A copious amount of potable water for a house and garden in Australia costs only about 1% of a family income. Obtaining and preparing a minimal 10 liters daily per person can be represent 20–40% of an average family household's economic capacity in Pakistan [6, 7]. For locals, most of these costs are invisible: there is no charge for water from public purification plants and women's labor is regarded as a free household commodity. Indeed, the notion that basic goods could be far cheaper in a wealthy country seems beyond comprehension. The cost of other services that rely on engineering (such as electricity supply and construction), taking into account total costs and comparable end-user service quality, were also much higher than in Australia, though the difference was not as great as for potable water which is heavy to transport.

For people in an industrialized country, many of whom have experienced low cost back packer holidays in the developing world, the notion that essential services they take for granted at home could be so much more expensive for people who have to live there also seems counter-intuitive.

Here is a startling illustration of the economic and social value of a reliable city water supply system providing potable water at high pressure 24 hours per day. Water supply utilities are large engineering enterprises. When they work well, engineering enterprises provide the products and services needed to maintain a civilized society at much reduced cost in terms of human effort and material resources. In other words engineers provide the means to achieve high levels of productivity. This frees up economic resources for all the other human activities that support a civilized society: law enforcement and security, justice, good governance, education, health care, and social services.

I had practiced and taught engineering for more than two decades, and until then I had never questioned the social and economic benefits of engineering. It was only when confronted by the absence of effective engineering that I began to understand the real value that it contributes to a society.

I was employing engineers in Pakistan and I became aware that I had to completely recalibrate my expectations for engineers' performance there, compared with my experience in Australia. I hypothesized that differences between Australian and Pakistan engineering practice might be a significant contributing factor. The near complete absence of research on engineering practice [8, 9] exposed the need for research to establish a body of evidence on practice in Australia and developing countries in order to test this hypothesis [10-12].

The research consisted of a series of mostly qualitative studies on engineering practice in Australia and South Asia informed by a combination of interviews, field studies and research visits.

III. STUDIES ON THE WORK OF ENGINEERS

In the 1970s and 1980s there were studies of engineers using the job analysis method revealing survey data showing, for example, that engineers spent about 60% of their time interacting with other people [13]. Several later studies of engineers explored social relationships between engineers and the wider structures of industrialized societies [e.g. 14, 15]. The rapid economic ascent of Japan relative to other industrialized countries during the 1980s motivated a series of comparative studies [e.g. 16, 17]. Sociologists interested in the details of daily practice have described many difficulties in studying engineers, such as technical jargon and the intellectual nature of critical aspects of the work which cannot be directly observed [18]. Most studies have been written for science, technology and society specialists (STS) and few are easily accessible for engineers or their educators, our primary constituencies. While these studies have contributed to our understanding of engineering practice, our knowledge of technical occupations remains tenuous and it is only recently that a comprehensive understanding of engineering practice with validity in a wide range of disciplines and settings has begun to emerge [e.g. 10].

Research literature on the social and economic value of engineering is even scarcer. A survey of introductory texts and engineering education research literature has exposed the near complete absence of any explanations that could be useful for students [19].

Recent research to build a comprehensive understanding of engineering practice has relied on observations of engineers in their workplaces [e.g. 10, 20-23]. Data from these observations could yield valuable insights on how engineers perceive the value of their work.

IV. RESEARCH METHOD

Qualitative research contributes rich data for an exploratory study of the ways in which people think about ideas. This approach has yielded valuable insights from systematic investigations of engineering practice. This study draws on evidence collected for earlier studies of engineering practice {Trevelyan, 2010 #1045}. Semi-structured interviews with a total of 120 practicing engineers in Australia lasting 90-120 minutes explored their careers, most aspects of their current work, and perceptions related to job challenges and achievement satisfaction. Some interviews included questions on dishonest behavior (of others), checking, and mistakes. In some instances, circumstances required small focus group discussions with up to three participants instead of interviews. Transcripts were prepared from recordings (with participants' consent) or notes (checked by participants). Several students contributed interview data using the same protocol with minor variations to suit their research on slightly different aspects of practice. Some also contributed field study data to triangulate the interviews. Training, joint interviews, and reviews of the recordings and transcripts helped ensure consistent data.

The sampling was partly opportunistic and partly purposeful for maximum variation to include engineers in all major disciplines, experience levels, and types of business (except defense). 6% were female and most had engineering degree qualifications.

Analysis followed standard ethnographic analysis techniques and also drew on the author's extensive first-hand experience of practice. Some recently published accounts from other research teams also helped triangulate data.

Instances of the word "value" and "benefit" in transcripts and field notes yielded a variety of perceptions that engineers have relating to value in engineering. This paper only presents a limited selection of the evidence analyzed for the research leading to this paper.

V. FINDINGS

Value can be a confusing idea, especially for engineers, even more for non-engineers listening in to an engineering conversation.

Many engineers use the word most often to refer to a number, the particular value of a variable quantity. Often the number represents an amount of money, for example 'dollar value' that might represent the total amount of money needed to purchase a machine.

Occasionally engineers referred to 'values' in the sense of personal integrity and honesty. This too can be confusing as many organizations now promote their 'values', building on the work of identity economists [24], because people whose identity aligns better with organizational values are more likely to display higher levels of motivation and loyalty.

Engineers often used the words 'value' and 'benefit' interchangeably to describe positive learning experiences for themselves or colleagues. Here a young engineer talks about the need to seek help from more experienced engineers:

"You can ask the most stupidest question it doesn't matter.. cause at the end of the day you are the one who is going to benefit from it...it is always good to stop and ask questions"

He has used the notion of 'value' or 'benefit' to refer to the personal acquisition of knowledge. Several engineers connected the word 'value' with detailed technical knowledge or information, or greater certainty, and in these cases the word 'benefit' was not used at all. Here is a process engineer talking about the earliest stages of engineering design:

"And then you move through to say a pre-feasibility, where you do a bit more engineering, solving some of the issues, defining some of the ideas and concepts and adding a bit more value to that number."

Here we see the word 'value' being used in association with 'number' but with an entirely different meaning from the notion of a number as a particular 'value' of a variable quantity. Here 'adding a bit more value' refers to the reduction of uncertainty in a number that represents an estimated technical quantity, in this instance the production capacity of a process plant. Engineers work with ever-present uncertainty from natural causes, the limitations of engineering science in predicting behavior of artifacts, and from the uncertainties of

human behavior. Reducing uncertainty, 'controlling risk' is a deep-seated value for engineers, as we shall see later. Safety, or the ability to reduce the chance of events that can cause harm to people, is also part of this engineers' concept of value, as the next quotation from a mechanical services engineer illustrates

"Ensuring that you select the appropriate equipment and appropriate way to develop the project that maximizes the value. It's safe and is efficient and conforms with ... (pause) ... engineering practice."

Although all engineers were asked to comment on discussions with clients or project sponsors, only three out of around 100 interviewed for earlier studies mentioned the idea of value in this context. All of these were the most senior engineers in their divisions of their firms. A senior software engineer talked about his difficulties in keeping design focused on the appropriate requirements:

"We have to make sure that the client's people understand how our systems will help them in their business. It's so easy for their ideas and ours to diverge, for our people to lose track of their needs and you end up with a system that produces little real value for the client. It's a constant struggle."

His understanding of value, in contrast to nearly all the other engineers, was firmly based in terms of the way the software behaved to produce economic value for the client.

One of the engineers who mentioned value in the economic sense identified that reducing uncertainty, usually described in terms of 'risk', was important in their work. This engineer linked 'value' with 'driver' to convey the notion of an important aspect for the economic performance of the project:

"One of the key drivers for the project – value drivers – was reliability."

In this particular project, failures would lead to extremely expensive production interruptions, both because of the cost of purchasing product from competitors to meet contracted customer delivery schedules, and the high cost of repairs to the equipment. This was translated into a need for high reliability from engineered systems being created by the project team.

The realization that describing the value that arises for their work could be a challenging task for many engineers led to two focused studies in a variety of firms. Twelve engineers described the relevance of business-related aspects of their work, including the economic value they create through their work. All found this issue difficult when it came to expressing it in words.

Two focus group discussions with five engineers in a technical consultancy revealed the difficulties that most engineers have with expressing notions of economic value emerging from their engineering work. When asked how they would describe what engineers actually do, one paused with a puzzled frown for several seconds, and then, when prompted that it might have something to do with "problem solving" that was a prominent feature of a company advertising poster displayed in the meeting room, he said:

"Yes, problem-solving, analysis... analyze systems... to make

things better, to make things more efficient."

When asked about the value created by the work they performed, there was another long pause. Finally, another engineer hesitantly said:

"Well, I guess the thing that the client wants most is the results so the value of my work is getting the results from out in the field."

Some of the engineers offered long-winded explanations that ended up at the same point: ultimately the client pays for a report or data. That, they said, would explain the value that emerged from their work.

The second study involved interviews with seven engineers at different firms, this time with more emphasis on business-related aspects of practice. Participants were asked about several aspects of commercial practice including value, negotiations and how they learned about business issues. Three of the participants had studied commerce in addition to their technical engineering degree course. All had difficulty expressing how commercial value emerged from their work. This chemical engineer firmly switched the focus on value back to technical certainty:

"For me, I don't really see value as a massive buzz word. I think there are better words. The word we always focus on is quality, which is basically how well you are able to deliver or exceed what someone is expecting of you."

Others mostly expressed commercial value only in terms of direct costs or time, or in achieving the project objectives without further elaboration. For example a graduate engineer with a few months of experience described value creation in these terms:

"It's making sure that the company does what it wants to do in the budgeted time and the budgeted amount of money, and ensuring that the skill set that I bring ensures that happens."

They also closely connected achieving objectives with 'enhancing shareholder wealth.' They also connected value with safety, a primary concern due to the high risks associated with their work, as seen in the following comments made by an oil field engineer (after the Macondo disaster in the Gulf of Mexico).

"Higher value is when you deliver something that's timely, it's what they wanted and it's been done without any safety problem or anything like this. I guess for me, in my job, the most important thing for me is safety. We work in an industry where there's a lot of potential for things to go wrong."

In discussing the concept of value, only one of the seven engineers in this second focused study specifically identified risk as a factor, a maintenance engineer with four years experience:

"What does the company stand for? It's adding value to the shareholder. I see that as two things: a finance return, i.e. making more money, or a reduction in risk because, if you think about it, all investors have a particular risk profile,

right? So if you can continue to reduce the risk that a shareholder has, whilst keeping the same rate of return, then obviously that's more attractive to more people."

He later confirmed that his understanding of risk and return in relation to investor preferences had been developed through his commerce studies. None of the other engineers with a commerce background made this connection.

In the earlier phase of the study before the focus on business aspects, only the most senior engineers had been able to connect technical work with creating value for clients. One cited an extensive design study for a mine in a pristine tropical location:

"I had to review the work done in the previous year. They had spent tens of millions on engineering, but they had added no value because they had not dealt with any of the ten showstoppers: risks that could cause a major release into the environment, mostly from flood events."

This engineer has directly connected the elimination of risks with increasing the project value for the client who was still seeking finance to implement the project. Yet the engineers working on the project seem not to have understood the link between the need to eliminate major risk factors and the availability of finance to develop the project.

VI. DISCUSSION AND LIMITATIONS

The data reveals that the notion of 'value' posed evident difficulties for the engineers interviewed in this research because of the number of different meanings that appeared in different contexts. These included the value of a variable, namely a precisely defined number, a notion of technical quality, an attribute of technical investigations that helped to clarify an appropriate choice from several different options, reduction of uncertainty, a personal attribute such as integrity, even an attribute that denoted useful learning from a personal experience. This last association was the main one that engineers associate with 'benefits'. Among these, the ultimate value of engineering work for a client or end-user is remote from the day-to-day considerations for most engineers: for most this value is associated with direct cost savings such as reducing the energy needed for a process, or the amount of labour needed, or simply achieving stated objectives. While most engineers see the reduction of uncertainty, usually conceived as the notion of risk, hazards, or threats to human safety, as a useful end in itself, only a few connect this idea with increasing the apparent value for an investor, client or end-user. Studying commerce can help engineers to see this connection, but does not seem to make it obvious. Even the entirely technical links between levels of uncertainty, design safety factors, and additional material weight and cost never emerged in interviews with engineers.

Another illustration that complements the data analysis came from an unexpected source. Engineers Australia are revising statements of competency [25] used to evaluate whether young engineers are ready to be admitted to chartered engineer status, the capacity for independent, unsupervised practice. Engineers Australia have used competency standards for this assessment since the 1990s. A near final draft released

for public comment in February 2012 after extensive consultation devoted an entire section to “creating value” in terms of advanced engineering knowledge – applying advanced theory-based understanding of engineering fundamentals, applying local engineering knowledge, investigating and analysing engineering problems, developing creative and innovative solutions, and evaluating the outcomes of engineering activities. While one of the suggested indicators that an engineer could use to demonstrate attainment of these competencies was “develop and apply new and emerging technologies, engineering applications and systems to create value for customer” the analysis presented earlier in this paper demonstrates that engineers are likely to interpret ‘value’ in this context in terms of technical quality rather than economic value.

As suggested in the introduction, a better understanding of economic and social value created by engineering work could help resolve several issues currently facing professional engineers.

Engineers enjoy a great deal of autonomy in their work. At the same time, engineers are often faced with open-ended tasks such as risk assessment and fault tree analysis that can never be fully explored in the time available. Engineers need to judge how far to pursue these investigations. Expectancy value theory [26] in its simplest form explains how choices to engage in activities are shaped by competency and value beliefs. In other words, engineers who perceive value in terms of technical quality and precision are likely to engage their technical competency in pursuit of quality and precision. This was observed by an engineering manager describing the difficulties of a project that was well behind schedule:

“the engineers were too involved in the design, the paper system, where the endgame is a railway product which has to be delivered”

An equally potent illustration arose from two studies on design checking and review in separate firms with demanding quality assurance regimes [e.g. 27]. The engineers regarded checking as “non-productive” and “work that added little value to the design”. Checking work was delegated to junior engineers, deferred, or relegated to the lowest priority. Some engineers complained that they did not have time for checking. As a result, engineers failed to detect mistakes in design documents leading to schedule slip, additional cost and time for rework and the risk of premature termination of a project. These unnecessary risk factors significantly affect the commercial performance of projects, yet this connection was not apparent to these engineers.

In both these instances, a better understanding of the economic value of technical engineering work might be helpful in refocusing the attention of engineers on tasks that are likely contribute useful economic value. While the engineers in the studies reported above were often devoting attention to the reduction of risk, they were less able to perceive commercial opportunities and financial constraints on projects such as the amount of finance available, cost of the finance, and payback period, all of which strongly depend on investors’ perceptions of risk.

A training course for junior engineers based on analysis of the interview data ran into unexpected difficulties with their ability to understand the commercial connections with their technical work. They were keen for their company to invest in their technical ideas, yet were unable to build a commercial case for their ideas based on risk perceptions. A discussion late in the course centered on the reasons why a client might employ a technical consultancy to perform a structural integrity review at a significantly higher hourly rate. Even though the facilitator provided considerable help, only one of ten engineers on the course finally managed to realize that a smart consultant could devise low cost ways to reduce failure risks, saving the client several times the total fee for the work. A careful review of the possible reasons for this difficulty after the course led to a decision to review engineering education curricula and texts. This review showed that the relevant technical and commercial issues were not addressed at all in most engineering programs [19].

Helping engineers to create more economic value from their work could also help with another issue perceived by many engineers: remuneration. Labor market economics predicts that remuneration is driven by marginal product, the value that workers contribute. It is possible that difficulties experienced by engineers in perceiving the economic value of their work, and hence engaging in tasks likely to contribute useful economic value, might be related to the widely reported steady decline in engineering remuneration relative to other professions.

Professional associations could help to develop an improved understanding of economic and social benefits provided by engineers working mostly out of sight, providing clean water, ubiquitous sanitation, adequate supplies of healthy processed food, telecommunications (without which most ‘technology’ would be merely of curiosity value), transport systems, robust buildings, healthcare and many other services. Some of the evidence presented in this paper might provide some useful ideas to publicize the social and economic contributions of their members.

The low rate of female participation in engineering in most industrialized countries is an issue that concerns many engineers. Female engineers have to tolerate direct and indirect discrimination to pursue their careers. Perhaps most women contemplating a professional career would prefer a profession with a clearly articulated social contribution. Lawyers fight for justice and doctors deliver healthcare. While engineers contribute to both, their contributions are mostly invisible and unrecognized. A better understanding of the social and economic contributions of effective engineering could help to change these perceptions.

Even though notions of value lie at the core of professional practice, the diversity of meanings and lack of coherent understandings on value in engineering discourse emerged late in this study. Further investigations focused on this issue may produce results that could answer questions raised by this research. One is the degree to which female participation in engineering is affected by espoused and implicit professional values. Ways to locate ideas on the value created by engineering at the core of curriculum require further investigation and experimentation.

VII. CONCLUSIONS

Analysis of interview data suggests that engineers' perceptions of value in their work primarily relate to technical quality and precision. To the extent that they perceived economic value, their perceptions are almost entirely limited to direct cost savings. In engineering practice, the word 'value' has a range of different meanings: it is easy for engineers using the English language to confuse the notion of 'value'.

Educators have a central role to play in helping engineers develop the ability to understand the economic and social value arising from their work. While social justice and caring has received increasing attention from engineering educators recently, one can argue that engineering must first produce tangible economic benefits before discussing how they might be shared between different stakeholders.

Educators could help young engineers appreciate that there would be few opportunities for engineers without investors who are prepared to entrust engineers with their money in the expectation of future financial and economic benefits. The evidence presented in this study suggests that studying commerce alongside engineering is not sufficient to enable engineers to understand the relationship between risk perceptions and financial constraints. Educators need to find ways to integrate an appreciation of uncertainty, risk perception, finance and the appropriate selection of technical options. Researchers need to rectify a lacuna of evidence in this aspect of engineering.

For most of the 20th century, the value of engineering in developing the power of industrialized societies and economies was unquestioned. Governments invested large resources in engineering enterprises though they demanded strict financial controls. [e.g. 28] By the end of the 20th century, however, economics had displaced political ideology as the primary determinant in political decision-making. Governments in most industrialized countries divested themselves their engineering organizations and now outsource their engineering from private sector providers. The commercial imperative now governs engineering priorities. This study suggests that engineers at the working level could benefit from a much clearer understanding of the links between their work and the perceptions of investors that make it possible.

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