Steps Toward a Better Model of Engineering Practice

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Abstract: *Accounts of engineering practice that explain the interaction between social and technical aspects are rarely cited in contemporary literature on engineering education. Further, these accounts have not yet contributed a simple model of practice which encompasses social and technical aspects. This paper presents a model of practice which is based on extensive qualitative and quantitative empirical data across a variety of engineering disciplines. The model explains the significance of social interactions as a means to obtain predictable performance from a large number of individually unpredictable human contributions and interactions.*

Introduction

Previous studies provide considerable evidence that engineers coordinate other people to deliver the products and services for which they are ultimately responsible (Faulkner, 2007; Lam, 1996; J. P. Trevelyan, 2007; James P. Trevelyan, 2008). Therefore we need to understand engineering as a social system in which people interact to create a product and service delivery organization. This social system, of course, is situated within a larger society which has been extensively studied from many different aspects and discipline frameworks. However, engineering practice has been rarely studied as a social system in it own right, partly because the language of discourse is technical and therefore can be difficult for outsiders to understand (Bailey & Barley, forthcoming; Barley, 2005; James P. Trevelyan & Tilli, 2007; Whalley & Barley, 1997; Zussman, 1985).

Engineering is a technical and a social discipline at the same time: the social and technical are inextricably intertwined. Yet the social aspects can easily be taken for granted. It is not easy to find literature which examines the interaction between these two facets of engineering practice. Several studies of engineering practice have demonstrated the significance of social relationships in many different ways. For example, Bucciarelli (1994) focused on design and explored the significance of social relationships within small firms working on technological innovations. Vinck and his colleagues explored the intimate links between social relationships and technical issues, again mostly in the context of design (2003). Faulkner (2007) examined the tension between the social and ‘technicist’ aspects of engineering practice. Korte et al (2008) described how early career engineers approached problem solving, learning that so much depended on finding people with useful information in an organization. Lam (1996, 1997) compared Japanese and British electronics firms revealing different approaches to the coordination of technical work.

The literature on engineering practice is rarely mentioned in contemporary writing on engineering education, possibly because it is widely dispersed, hard to find, and often written for non-engineering audiences. Engineering educators appear to be looking for a structured view of engineering practice which could provide some guidance for dealing with the current difficulties perceived by many writers. For example, Sheppard *et al* (2009) recently advocated that engineering education should be centred on professional practice and that only radical redesign will result in effective reform of what is currently a “dysfunctional system” (xxii-xxiv). Williams (2003) argued that engineering has lost its identity because design has been lost to artists, architects, programmers and specialist industrial designers, and the social interactions have been lost to management studies.

This paper argues that studies of engineering practice can provide a unifying model of engineering which could provide a sound base for education and an engineering identity without the need for radical redesign. Engineering works. It could work better, however, with improvements in education and an identity in which the social and technical embrace each other with equal prominence.

Taking the next step, however, requires a detailed examination of engineering practice across many different disciplines.

Method

Data for this study has come from transcripts of more than 90 semi-structured interviews with a broad sample of participants in different engineering disciplines, notes on extensive first-hand observations of engineering practice, and similar data from colleagues (Domal & Trevelyan, 2008; Gouws & Trevelyan, 2006; Han, 2008; Mehravari, 2007; Nair & Trevelyan, 2008; Petermann, Trevelyan, Felgen, & Lindemann, 2007). Most interviews were recorded and full transcripts were used for analysis. In cases where recordings were not available, the transcript reconstructed from notes was checked by the respondent for accuracy.

Trevelyan (2007) presented a fully detailed description of the interview method, qualitative analysis and validation. Analysis of interview transcripts, field notes and other reference texts followed standard ethnographic techniques (e.g. Huberman & Miles, 2002; Strauss, 1987). Similar methods have been used by earlier researchers studying engineering practice (e.g. Bucciarelli, 1994; Vinck, 2003; Zussman, 1985). Their published data together with independent field observations provided extra data to 'triangulate' the interviews (providing independent evidence and any indications of aspects of practice that might have been overlooked). In addition, analysis results have been discussed with some of the participants and other engineers to provide additional assurance that the results are trustworthy and meaningful.

Qualitative analysis using a grounded theory approach led to 84 descriptors for aspects of engineering practice and 62 for specialized knowledge {see Trevelyan, 2008 #555, updated with further details at http://www.mech.uwa.edu.au/jpt/pes.html}. Great care was taken to devise discipline-independent descriptions that can transcend discipline boundaries.

The resulting framework of descriptors guided the construction of on-line surveys used in a longitudinal study of 160 engineering graduates from a single year cohort from The University of Western Australia (Tilli & Trevelyan, 2008). About 80% of the original sample are continuing to participate after two years of quarterly surveys designed to find out what they are doing and learning. These surveys have confirmed that these descriptions are meaningful to engineers in the majority of disciplines, and that together they represent a comprehensive coverage of their work (Tilli & Trevelyan, 2008). While there were some significant differences in the proportion of time spent on different aspects between different engineering disciplines, the overall pattern was remarkably consistent.

Individual engineers that we have observed and interviewed fit into this model, but seldom develop expertise all aspects of practice, even in a long career. Some individuals focus just on a few aspects, such as modeling, procurement or project management. All participants have been observed to engage in some aspects such as technical coordination (J. P. Trevelyan, 2007). Analysis of interviews and field notes, backed up by observations from quantitative surveys, tells us that most engineers, at any given phase of their career, experience about 50% of the aspects of engineering practice that we have identified. Only a few of these seem to depend on experience level.

This complex framework has to be simplified in order for it to be useful. A second stage of analysis has led to a coherent and comprehensive description which describes the different aspects in a manner which allows engineering practice to be understood as a human sociotechnical system. The remaining sections of this paper present some of the results of this analysis.

A Unifying Model of Engineering Practice

It is necessary to start with a contradiction: engineering practice is the resolution of the predictable with the unpredictable.

On the one hand, engineering practice is based on the application of known principles, mostly based on the physical sciences with increasing use of biological and life sciences. These principles enable engineers to make accurate performance predictions, especially at the limits where failure becomes likely. They also enable engineers to quantify uncertainty: the relative magnitude of what is not known or quantifiable.

On the other hand, engineering practice is a human performance at all levels, from trades to finance, and human performance is intrinsically unpredictable. Social interactions often occur entirely by chance. For example, two people from different floors in the same building may coincidentally feel the need for a better quality cup of coffee and meet across the street, and in doing so remember a technical issue on which one had promised to respond and the other had forgotten to follow up.

Engineers are rewarded for predictably organizing the delivery of products and services on time within agreed resource budgets, both of which are usually near the minimum possible. In some fields of civil engineering construction, for example, profit margins can be less than 1%. Yet the completed building represents the results of perhaps millions of individual human actions, each of which has an element of unpredictability.

Engineering practice, therefore, provides the means by which specialized technical products and services can be delivered predictably from intrinsically unpredictable human performances and interactions. Within this conceptual framework we can find many familiar elements. Engineers start by understanding client needs and conceiving technically and commercially effective solutions. They help clients make informed choices based on outline designs. Accurate predictions, based on engineering science with clearly understood uncertainties, adjusted from experience by engineers with a reputation for reliable predictions, provide the confidence that investors need to commit finance. Engineering usually provides returns long after the original investment is made so this confidence is crucial at the outset. With an investment decision in place, detailed design and planning precedes project execution and delivery of the agreed products and services.

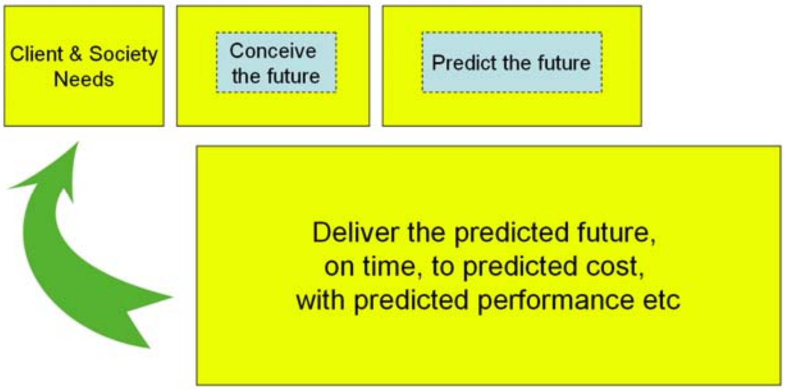

Figure 1: A Simplified Model of Engineering Practice

Figure 1 illustrates this model. The upper level represents the prediction stage. Starting with an understanding of client and society needs, engineers conceive future solutions and make predictions on which investment decisions can be based. The delivery stage at the lower level aims to make those predictions come true, and the experience (and often the lessons learned from difficulties overcome) helps to improve the prediction stages for subsequent projects (symbolized by the feedback arrow). In engineering practice, the delivery stage nearly always takes more time, resources, attention and effort than the prediction stage.

By focusing on engineering practice predominantly in terms of problem-solving and design, contemporary engineering educators are restricting their interest to the sections of figure 1 outlined with dashed lines. "Engineering practice is, in its essence, problem-solving." (S. D. Sheppard et al., 2009, 3) "Engineers are hired, retained and rewarded for solving problems." (Jonassen, Strobel, & Lee, 2006) The CDIO manifesto (Crawley, Malmqvist, Östlund, & Brodeur, 2007) was a notable attempt to break away from this narrow perspective by emphasizing the implementation and operation parts of engineering practice. However, their experience shows that this is not easy, because one has to recognize the critical prominence of social interactions in order to achieve this.

'Problem-solving' can be also interpreted in a wider context, of course. With a broad enough understanding, any expert performance can be understood in terms of problem solving (Ericsson, 2003,74-75). However, once translated into the narrow confines of a technical domain, problem-solving can easily be reduced to an intellectual exercise comprising a mechanistic sequence of logical steps. It is then easy to lose sight of the social reality in which real results have to be delivered (Jonassen et al., 2006).

A Sequential Model

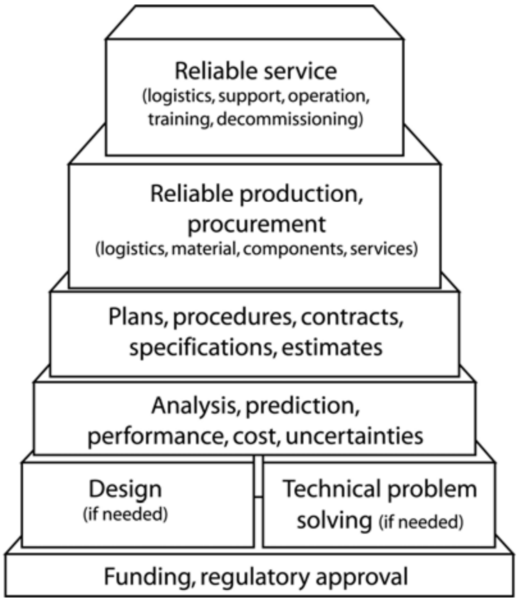

Figure 2: Sequential Stages in Engineering

Figure 2 illustrates engineering practice as a vertical sequence of stages (starting at the bottom: each stage builds on the results from the lower stages). In practice, funding and regulatory approval precedes each of the main stages through a “phase gate” decision making process which is usually unique to a particular organization (Cooper, 1993; Huet, Culley, McMahon, & Fortin, 2007). Different engineering ventures naturally have different emphasis on each the stages. For example, in the context of an engineering consultancy, design documentation may be the product and construction supervision may be an optional service. Plans, procedures, contracts, specifications and estimates would still be a critical stage.

Many aspects of engineering practice identified in interviews and field observations remain invisible and cannot be directly related to the blocks shown in figure 2. The majority of these constitute work that many engineers regard as ‘not real engineering’ (Perlow & Bailyn, 1997, 232-235). Figure 3 represents similar activity to figure 2, but this time we are looking at a cross section to expose what is not visible in figure 2. What we see in figure 2 is only the ‘top deck’ of engineering practice: figure 3 shows the other decks that provide the ‘structure’ without which the top deck would never remain intact. The size proportions of the different ‘decks’ correspond to the relative significance of each aspect, derived from both qualitative analysis and quantitative time perceptions. From this we can see that, like an iceberg, the invisible engineering aspects are much more significant than the top deck. Technical engineering work represents, at best, only two ‘planks’ of the top deck. We can now begin to appreciate just how limiting it is to see engineering practice only in terms of the technical.

These ‘invisible’ aspects of engineering practice have evolved over time to control all the uncertainties and unpredictable elements of engineering practice that arise because engineering is social system.

Many engineers find it hard to predict even their own their work. Between scheduled meetings they react to problems as they occur so the results from their work will be unpredictable (J. P. Trevelyan, 2007, p194). 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 to work on each day, or when.

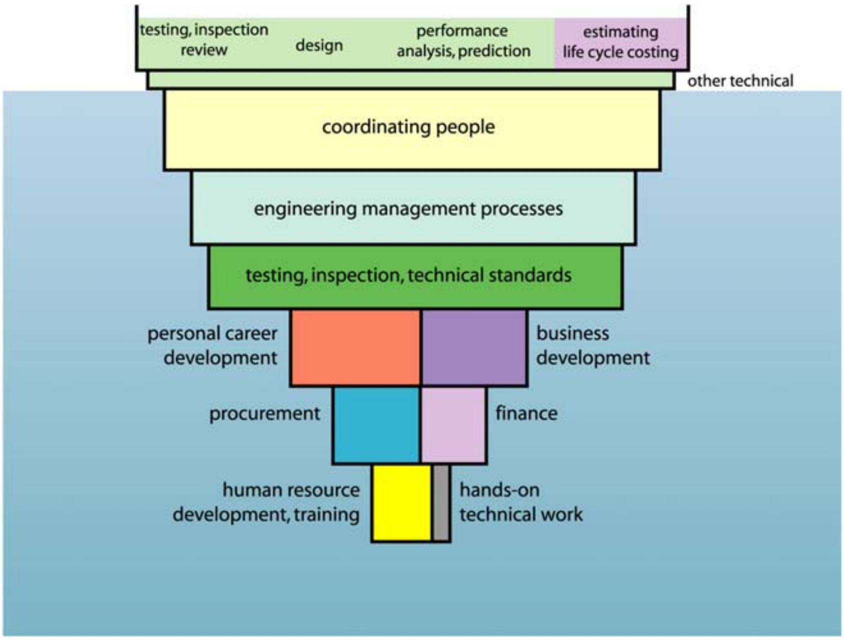

Figure 3: Invisible Engineering

These hidden aspects of engineering practice provide a measure of predictability for the end results of individually unpredictable performances by the participants. For example, one of the ‘invisible’ aspects of engineering practice is helping engineers comply with appropriate technical standards to reduce the chance that mistakes will be made, which would not be picked up in time. Technical standards have been created through experience by engineers and are carefully negotiated within each specialized engineering discipline, striking a balance between restrictions to promote safety, ease of use, and avoiding constraints that would inhibit innovation and design freedom (Shapiro, 1997).

Analysis of interview transcripts and field study notes examining text passages that mentioned specialized knowledge, using a grounded theory approach, yielded 36 different types of technical knowledge and 26 types of business knowledge. This list includes all of the categories mentioned by previous accounts (Bailey & Gainsburg, forthcoming; Eraut, 2000, 2004; S. Sheppard, Colby, Macatangay, & Sullivan, 2006; Tenopir & King, 2004; Vincenti, 1990). About half of the knowledge categories do not seem to have been included in the earlier accounts, for example failure modes and symptoms, containing errors, and many aspects of business know-how such as intellectual property. No individual can acquire this range of expertise. Engineering practice, instead, relies on distributed expertise and cognition (Jonassen et al., 2006, p144). The social process by which this expertise is shared contributes a significant proportion of the hidden layers in figure 3, and helps to explain why building relationships with experienced engineers is so critical for early career engineers (Lee & Smith, 1992).

Figure 4 combines the invisible elements of figure 3 with the sequential process shown in figure 2. The sequence of steps common to most engineering activities are enclosed within a scaffold which continually guides the implementation steps towards the intended objectives. A web of social relationships enables individuals which are part of the encircling social system in the scaffold to influence and coordinate the technical process of human activity. The scaffold helps to produce predictable results even though each of the human contributions is unpredictable. The scaffold consists of informal processes grouped on the left and their formal equivalents on the right hand side.

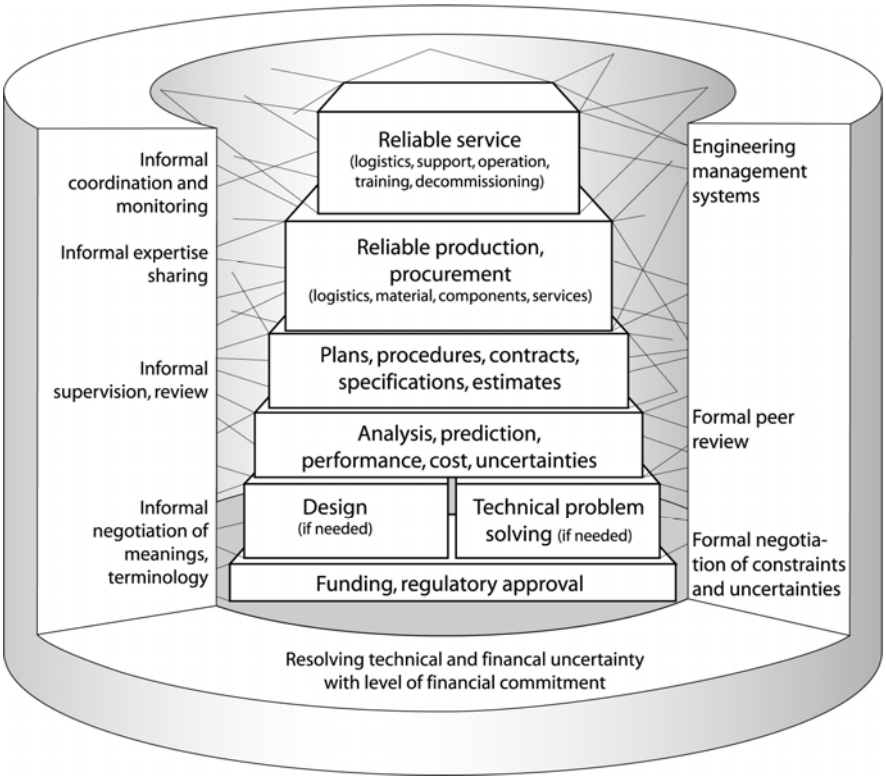

Figure 4: Visual Representation of Engineering Practice

Notice how the scaffold also provides the foundation: this is intentional. The scaffold involves continual interaction between all the participants, including the client(s), financiers, engineers, contractors, suppliers, production and service delivery workers, technicians, regulators, government agencies, local community and special interest groups.

Within the scaffold base, the work starts with negotiations on constraints, even before funds have been committed. Constraints include:

- capabilities of suppliers, production capacity
- technical requirements
- schedule
- regulatory requirements
- safety & health 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 committing funds at each stage of the project.

At the informal level, there is continuing negotiation of meaning. 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 it means a non-negotiable statement of requirement: 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 their components would have lower performance. Some people may understood a specification to be ‘elastic’: as long as the really important requirements are met, other non-compliances could be negotiated away in the form of a price discount, 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 scaffold processes construct their own knowledge and understandings in different ways and the process of sharing it can be lengthy and difficult at times.

On the formal side, we find engineering management systems, for example project management, configuration management, environmental management (e.g. ISO 14000 series), health and safety management (e.g. ISO 18000 series), quality management (e.g. ISO 9000 series), asset management (or sustainment), document management and change management.

Conclusion

The engineering education literature and recent attempts to codify engineering education outcomes (e.g. American Society of Civil Engineers, 2008; Crawley et al., 2007; S. D. Sheppard et al., 2009) seem to be based on notions of engineering practice which differ from published observations. Published literature demonstrates the critical importance of social interactions but, so far, has not produced a simple and coherent model of engineering practice which fits the available data. This literature is widely dispersed, is not easy to find and has been mostly written for non-engineering audiences. This paper provides a model for engineering educators which is based on extensive empirical data and fits other published accounts of engineering practice. However, since much of the model is unfamiliar, beyond the problem solving and design components, more detailed descriptions are needed before educators can build on this work.

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