Chapter 13
Tensions in Developing Engineering Design Competencies

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Abstract Engineering design competencies and the role of scientific disciplines in engineering curricula form the background for this chapter. Engineering knowledge as produced in the context of engineering education at large is seen as the key to understanding the dominant strategies of machination in engineering practice. At the same time, there is a need to bring new perspectives to engineering design and to the understanding of engineering knowledge. The crowding of engineering education with an exploding number of new specialities and disciplines has rendered problematic the broad 'polytechnics' education prominent in the traditions of engineering education. While the idea that engineering is building on a natural science base is still dominant as the common model for the education and identity building of engineering, the growth in specialties and required competencies are blurring the claims by engineering schools and institutions of a common engineering identity. Social sciences and humanities primarily have functioned as an add-on to the rather diverse engineering curricula at the same time as new ways of understanding technologies as hybrids constructed through historical and situated actors associations have created a new ground for interdisciplinary integration. In design engineering education, these new types of knowledge have become foundational for their approach to technology.

Keywords Engineering design • Education • Competence • Practice • Science discipline

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Introduction

By the 1990s, basic questions had been raised in both the United States and Europe about the relevance of engineering education as it had developed since World War II. The issues included a lack of practical skills in modern engineering training, a mismatch between the needs of industry and the sciences being taught, and the actual analytical qualifications being awarded in engineering education compared with visions of engineers as creative designers and innovators of future technologies. With its emphasis on science and knowledge structured around technical disciplines, engineering education developed into an education of basically technically skilled cooperative workers rather than innovative and creative designers of technology for society. The knowledge and broad innovative capacity needed to produce creative design engineers able to cope with contemporary technological changes were seen as missing in engineering education.

Several educational initiatives have addressed these issues, outlining plans to reform engineering education. Some focus on the engineering curriculum or the pedagogy and learning modes employed; some develop completely new engineering programmes based on new technologies. Other initiatives combine business, management, and organisational understanding with engineering or alternatively emphasise the creative and design aspects of engineering.

Critical accounts by observers close to the situation point to the need for reform in engineering education (Williams 2003). Some critics seem confident in the achievements of engineers in society and argue for the continuation of a traditional science-based engineering curriculum (Vincenti 1990; Auyang 2004). However, they do not raise critical issues related to the social and institutional dependencies of technology. Engineering schools and professional institutions have supported the idea of a close relationship between science and technology by asserting that natural sciences form the core foundation of engineering. At the same time, contemporary developments in the natural sciences and engineering sciences have blurred the boundaries. New approaches to techno-science seem to be gaining ground as characterising the ties between modern science and technology, leaving neither one in a subsidiary role (Ihde and Selinger 2003). These new approaches recognise the role of technology as a contributor to scientific achievements and change the basic idea of nature and technology. A key question is whether these accounts are satisfactory in understanding and coping with contemporary problems in engineering education in relation to the demands on engineering practice at large.

Two basic elements are important to understand contemporary challenges to engineering knowledge and design practices. One relates to the demand for engineering competence and engineering solutions in industry and society. The other relates to the institutional developments in engineering schools and the role of engineering sciences in relation to objects of technology to be handled by engineers. The approach in this chapter will be to (1) identify historical developments in technology and its social embedding and the role of engineering institutions in this relation and (2) build a theoretical framework to better understand engineering knowledge and competence and how they challenge the role of education. The three following sections will outline tensions in the research and educational agendas of engineering institutions following the visions of engineering science and its controversial relationship to engineering practice and consequently the gap between engineering practice domains and engineering curricula. The subsequent four sections start with a new focus on engineering competence in order to present both the critique of engineering education and visions of new modes of learning and a design focus in engineering competence building.

A Science Base for Engineering

In order to understand today's situation, we must consider one of the most important historical changes in engineering education – the construction of a science base for engineering. This development resulted partly from the increase in public and military funding of engineering research during World War II, partly from attempts to develop a more theoretically based foundation for engineering. The endeavours to establish a science base for engineering created an elite group of theory-oriented universities and technical schools of higher education in both the United States and Europe (Reynolds and Seely 1993).

Until the early twentieth century, a rather deep gap existed in engineering curricula between science classes based on high degrees of mathematically formalised knowledge and the more descriptive and less-codified technical subjects. Controversies resulted in positioning technical sciences as secondary, or applied, in relation to the natural sciences. Technical universities, at least in Europe, were restricted from giving doctoral degrees and addressing scientific matters without the support of university faculty versed in the natural sciences. However, the new era of expanding technical sciences lessened these controversies because of its increased focus on innovation and awareness of the close interactions between specific areas of science and technology.

A leading institution in this change in the USA was the Massachusetts Institute of Technology (MIT). Although engineers made significant contributions during World War II, the success of the Manhattan Project put physicists in the spotlight. Savvy engineering leaders recognised that the path to prestige lay in a closer emulation of scientists. In Europe, this orientation towards a scientific basis for engineering already had a long tradition in the intellectual environment around the elite institutions, especially in France and Germany. The post-war tendency towards formalisation of science councils and large government-sponsored research programmes centred on the peaceful utilisation of technologies developed during the war and spurred a dramatic increase in research at technical universities and a change in the methods of teaching engineering.

Sponsorship of fundamental studies in a variety of areas supported the trend away from practice-oriented research and education resulting in critique from industry (see, e.g. Cohen and Zysman 1987; Dertouzos et al. 1989). Successes in fields such as high-speed aerodynamics, semiconductor electronics, and computing confirmed that physics and mathematics, conducted in a laboratory-based environment, could open new technological frontiers. Military research during these years also tended to focus on performance – increased power, higher altitudes, and more speed – goals that were conducive to scientific approaches (Reynolds and Seely 1993).

The post-war decades saw the rise of systems engineering and thinking as broadly applicable engineering tools (Mindell 2002). Systems sciences that include control theory, systems theory, systems engineering, operations research, systems dynamics, cybernetics, and others led engineers to concentrate on building analytical models of small-scale and large-scale systems, often making use of the new tools provided by digital computers and simulations (Hughes and Hughes 2000). Some within engineering even found that these tools might finally provide the theoretical basis for all engineering that goes beyond the basic principles provided by the natural sciences.

Changes in the foundation of engineering education, with the expansion of science-based technical disciplines, also led to changes in the curricula of traditional vocational schools of engineering. Though with different names, 'polytechnics' in the United Kingdom, 'fachhochschulen' in Germany, and 'teknika' in Denmark shared common characteristics in recruiting students from groups of skilled technicians and supplementing their training with a theoretical education while maintaining a focus on industrial practice. As a result, the schools inherited the experience-based and practical knowledge and skills of students who had previously worked as apprentices in construction firms, machine shops, and industry. During the 1960s, the curricula of these technical schools were expanded. Typically, these changes included improvements in mathematics and natural sciences by copying the science base from engineering universities.

At the same time, the decline in the apprenticeship training of craftsmen and skilled workers began to undermine the recruitment lines of the polytechnics (Lutz and Kammerer 1975). While this type of engineering education was well supplied by the traditional, smaller craft-based industries, the increasing size of industries led to a change in the ways the workforce was trained, resulting in increasingly specialised machine-shop skills. Fewer candidates had the necessary broad skills and apprenticeship training required by the engineering schools. Consequently, the schools were forced to establish other recruitment systems to survive, leading to a complete reversal of the basis for recruiting students during the 1990s.

As a result, the overall trend towards a more science-based curriculum becomes dominant in all parts of engineering education.

Transfers from Engineering Practice to Scientific Discipline

The structure of many engineering institutions still shows the remains of the big four in engineering – civil, mechanical, chemical, and electrical – that date back to the nineteenth and early twentieth centuries. Electrical engineering was the exception almost from its origins in the early twentieth century. In this engineering discipline, the relationship between theoretical teaching and industrially developed technologies was closer than in other engineering domains.

Yet today, many engineering departments still have their core activities defined by technical disciplines, such as mechanics, energy systems, electronics, chemistry, building construction, or sanitary and civil engineering. Many of these disciplines were related to specific problems and industries in their founding years, but as the demand for science-based research and teaching became prominent, the original roots to practice and industry declined in significance. With the changing demands, more abstract courses defined by new scientific approaches and specialised fields were developed.

In the course of history, many engineering disciplines have developed from what could be called an encyclopaedia stage, dominated by descriptive representations of technological exemplars, into a more abstracted and theory-based scientific stage (Latour 1987; Jørgensen 2003). This latter stage adds the strength of applying model descriptions, including mathematical representations and topic generalisations. However, in the transformation process, concrete experiences and practice-based knowledge, embedded in specific technical solutions, has often been lost. Consequently, the transition represents a movement from scattered collections of representational exemplars to more complete representations of the technologies in question, documented by constructed theories and models. At the same time, the transition represents a movement away from the engineering practice and experience needed to make technology functional (Gibbons et al. 1994).

Contemporary tensions in engineering education are spurred by the diversity of modern technologies. The applications of these diverse technologies throughout society require increasing differentiation in the education of engineers. The diversity presents new challenges to the sense of unity, identity, and standardisation of professional preparation in engineering institutions. Despite the complexity and multiplicity of technologies, institutional unity and its manifestation in a common engineering core curriculum have so far been successfully maintained by the engineering profession and by elite engineering universities.

Nevertheless, the policies of identity formation and the creation of a homogeneous image of engineering are issues that need to be taken seriously, both in historical accounts and in contemporary reform initiatives. Engineering identity plays a vital part in both arguments for and against educational reform in negotiations about engineering educational reform. The battle over engineering identity is closely linked to the significant role assigned to core disciplines of natural and technical sciences as defining the common ground for engineering, the add-on role of non-technical topics as well as the controversies over the relationship between science and practice.

Engineering Domains Versus Discipline

Early in the twentieth century, the idea that engineers have societal responsibility and are the heroic constructors of the material structures of modern society was being supplanted by a less heroic and more mundane image of engineers as the servants of industry. This image of engineering reflects a reduction in the influence of engineers on the direction and content of technological innovation and supports the positioning of engineers in a less influential and subordinate role in their attempts to promote business interests, which is maybe closer to engineers' self-image in contemporary society. The description of an engineer's contemporary competencies might include the following: 'scientific base of engineering knowledge', 'problem-solving capabilities', and 'adapt knowledge to new types of problems'. The focus is more often on problem solving and less on problem identification and definition (Downey 2005).

Engineering problem solving most often is related to intentional goals, where the job is to handle a practical situation either by constructing an artefact, modifying existing solutions, or identifying the reasons for certain failures. The aim is not, like in most scientific endeavours, to establish a deeper and more theoretical substantiated understanding of the problem in focus but to produce working solutions and test them in accordance with existing knowledge of performance and eventual risks. It is the solution to the present problem that is important and independent of eventual limitations to the existing knowledge; the practical imperative is to identify a solution (Jakobsen 1994).

Engineering problem solving is characterised by the organisation and resources framing the situation (Noble 1977; Roe-Smith 1989), the heterogeneous character of the involved and relevant knowledge (Hård 1994, 1999), and the hybrid (Latour 1993) – and even sometimes complex – character of the resulting solutions. Problem solving involves knowledge from different domains of engineering practice and knowledge from different disciplines as well as combining these with practical experience and existing routine solutions. By tradition, there has been a tendency to emphasise knowledge produced by the natural and technical sciences as the most important for engineering, while contributions from other disciplines are taken into account more in line with practical experiences. This contradicts the experience from many studies of technology demonstrating that the objects of engineering practice very often are hybrids synthesising knowledge coming from both the sciences and the social context and the users' (involved actors') association of meaning assigned to the intended functional and symbolic entities of the resulting technologies (Sørensen 1998).

Engineering problems are often only vaguely defined and involve an important first step of analysis and clarification. Problems are not just pre-given but may need refinement or even critical analysis of the situation or the context seemingly producing the problem. This process of problem identification and definition involves non-trivial reasoning to assess the relationship between the problem and potential strategies for creating solutions – to solve the problem. This will often result in a redefinition of the problem and also a critical assessment of the availability of useful solutions (Downey 2005). This process creates a reduction from the anticipated problem(s) to the 'solvable' technical problem or as in many cases a complex construction and disciplining of artefacts and uses.

Not only the problem at stake may turn out to be vague and require a process of stabilisation but also the involved spectrum of solutions and the involved types of knowledge can vary a lot. The problem-solution relationship may as such be open ended, but the demand for solutions in engineering practice is evident, and the choice of methods and knowledge leading at least to some solution is therefore an intrinsic part of engineering. While most professionals may tend to use the knowledge they command, the spectrum of relevant solutions may be broader, and there might be a need to develop other solutions.

The heterogeneous character of engineering knowledge used in practical problem solving involves both codified knowledge based on explicit theories and models and methods and experiences based on prior work and knowledge about artefacts and situations. Codified knowledge can come directly from scientific disciplines and from standards developed in a historical process, but it can also be embedded in the knowledge of experienced engineers as a competence that unfolds as a repertoire of principles and routines transmitted through specific solutions and practical approaches (Ferguson 1992; see also Boshuisen and Schmidt 1992; Barnett 1994). This results in theories, methods, and practices representing rather different levels of idealisation, specification, and documentation.

While codified knowledge is based on reduction and specification and can be transferred in texts, models, etc. (Polanyi 1958; Kuhn 1970; Henderson 1999), the practices and routines involved in the repertoires of experienced engineers – the expert knowledge – is often less precise, dependent on the context recognition, and therefore also more difficult to transfer to others (Schön 1983; Jakobsen 1994). Engineers are supposed to handle several processes, including understanding situations and contexts, finding relevant solutions, and balancing technical and non-technical demands. This is where the routines and heuristics become crucial for the outcomes of engineering, and the competent professional seems to solve problems better (see, e.g. Patel et al. 1991; Barley and Orr 1997).

Engineering is performed in an organisational context already implying certain divisions of labour and specialisations in problem-solving activities. This also implies framing of the building of experiences and learning processes through practice. Such framed situations of problem solving and organising of engineering activities can be characterised as ‘engineering practice domains’. These domains presuppose a certain stability of the activities to make the transfer of experiences and problem-solving practices possible, though still difficult as mentioned above. An engineering domain is consequently defined as a stabilised collection of knowledge and practices organised in relation to a collection of problem-solving activities with a common base of technologies, artefacts, and routines. Domains will typically have certain common features that resemble the phenomena identified as ‘communities of practice’ (Wenger 2004), including identity and a set of standardised collection of problem-solution relations. In some cases, certain engineering science disciplines may be involved in the boundary definition of a domain, but they can only explain parts of these boundaries and the competencies involved. Also the notion of ‘mode 2 knowledge’ illustrates facets of engineering practice domains (Gibbons et al. 1994) and the continued process of change involved, especially in the case of new areas of knowledge like information technology (IT), food technology, biotechnology, and environmental management.

In contrast, the codified knowledge produced and transferred in the engineering science disciplines is based on a historical process of idealisation and reduction of the objects of study involved. While their origins often can be traced back to certain more practical problems and even distinct technological objects, the process of creating a codified science and the idealisation of the objects handled in theories and laboratories represent both the strength and weakness of these technical science disciplines. They were created in the search for more specific knowledge and solutions giving rise to theory formulation and optimisation of certain aspects of technology, but they also developed into rather autonomous knowledge communities with their own – potentially dogmatic and specialised – views of the problems to be solved, even to the point of developing their own epistemic cultures (Knorr Cetina 1999).

The role of engineering practice domains and the idealised character of technical science disciplines render engineering knowledge particular and local in its reference and dependency on specific technologies and their practical utilisation. This is countered by a continued production of standardisation procedures and a worldwide exchange of knowledge, which attempts to overcome local delimitations and to establish global technological knowledge regimes. Consequently, engineering institutions are part of a global constitution of social-ordering mechanisms installed through dominant technological solutions – a situation that results in global controversies over the choice of technologies.

A New Focus on Engineering Competence

Competence has become a significant focus in educational policy as well as industrial policy during the last 10 years. While earlier discussions concerning the design of education have been concentrated on such concepts as ‘multiple intelligence’, ‘qualifications’, ‘understanding’, or ‘abilities’, the new focus on competence is a product of wider societal developments. Competence emerges as institutions experience a widening distance between what is honoured and valued by the university and academic institutions, and the effects desired and valued by users of academic labour, producing growing interest in the ability to understand the relations between educational practices and the actual usefulness of candidates in business, politics, and industry. This reflects the outlined discrepancy between engineering practice domains and the disciplinary knowledge dominating engineering education.

One of the dynamics behind the interest in competence is the ongoing proliferation of the practical arenas of engineering. Technology is not only complex in the sense that a technological development arena comprises multiple strands of engineering specialisations. Technology also tends to be complex as reflexivity inscribed in technological development transcends professional boundaries and creates a demand for new types of knowledge, skills, and abilities. It is definitively not adequate to the modes of design education that cram the heads of engineering students with pieces of knowledge in the hope that, on their own, they will be able to find the right pieces on the shelves when they need them in their professional practice (Beder 1998).

The essence of the concept of competence is to create relations between the production of knowledge, skills, and abilities on the one hand and the practical usefulness of knowledge, skills, and abilities on the other. Moving from qualifications to competence emphasises the differences between the goals for an educational practice and the goals for a professional practice. Concern for competence acknowledges the fact that knowledge manifests itself differently depending on context, situation, and perspective. It is thus the relations between the components of knowledge and the actions performed in actual situations that are crucial in evaluating competence, not the elements of knowledge or the resources for action in themselves.

The characteristic of engineering competence is the unfolding of knowledge, skills, and abilities in a concrete practical setting where it unfolds with the relevant aims, qualities, and values culturally inscribed. This gives engineering competence the following basic characteristics (Jakobsen and Munch 2005):

- Competence is relational and contextual; that is, it is a perspective on personal performance in a context also involving organisation, norms, values, instruments, aims, and intentions.
- Competence involves the process of realisation and therefore the resources creating conditions and arguing for relevance, demanding the possession of attitudes, motives, drive, intuition, and communication.
- Competence is knowledge, skills, and abilities in a form and structure used in practical problem solving. This implies that competence relates to an authentic practice (distinguished from a designed practice).

In an educational practice, this implies that competence elements must not be separated but rather placed in a context. Knowledge and methods cannot be developed independently of the object and context to which they are connected. To have a meaningful learning process, the competence elements must be placed in relationship to each other and to the concrete question, selected universes within the discipline, professional routines, etc.

Machination and the Idealised ‘Blinded’ Eye

The critical relations between engineering practice domains and techno-scientific disciplines can be illustrated with four examples taken from different areas of engineering: (1) wind turbine development and the role of aerodynamics, (2) the identification of environmental objects of regulation, (3) formalised design methods and the role of design creativity, and (4) knowledge management and the assumptions of knowledge in practical use.

1. When the recent phase of wind turbine development started in 1970s following controversies about nuclear power and the use of fossil fuels, many researchers and policy planners – including experienced engineers and industrialists – shared the view that wind turbine design and production was a ‘low tech’ and

well-understood technology. In this context, the role of aerodynamics was considered to provide the science base for designing the rotor blades for the turbine building. This view drew on the quite substantial engineering activities carried out in the aeroplane industry and its research facilities on the aerodynamic problems and behavioural phenomena related to the design of wings, propellers, and the body parts of the planes. Though there were limitations to the understanding of turbulence and non-smooth flows, these problems were seen as related to extraordinary weather and operational conditions – eventually relevant in the design of supercritical aeroplanes – but not problems that would disturb the design of wind turbine blades and towers. The knowledge gained from experiments and measurements of wing profiles in wind tunnels (Vincenti 1990) was seen as a historic pathway to the now science-based understanding of the design principles. But this assumption proved to be wrong, as experts from Boeing and NASA later concluded. Some of the most advanced wind turbines designed on the basis of these principles broke down after short periods of operation and did not turn out to be very energy efficient (Jørgensen and Karnøe 1995). The aerodynamic problems and the loads on the structures in wind turbines were much more critical than expected. In the decades following the first experiments, a more complete picture of the specific phenomena involved in the aerodynamic operation of wind turbine wings could be established. In a sense, the differences in operational conditions between airplanes and wind turbines were simple and striking but not enough to raise questions about the generality of aerodynamics among the research-based engineers. The practical design of wind turbines, for example in Denmark, was based on test runs and small steps upgrading from one design to the next. The design work followed a distinctive pathway that took into consideration the operational conditions of wind turbines, including attention to extreme stress conditions from vibrations and unstable wind pressures along the wings and between them.

2. The key to the second example lies in the issue of environmental science and engineering taking the environment for granted as those aspects of nature that are relevant to human living conditions. Identifying environmental objects of regulation turns out to be a much more undetermined and politically influenced process in which identifying the sources of recognised pollution phenomena or health problems becomes quite complex and difficult. This complexity becomes evident not only in the problem of identifying relationships between cause and effect but also in the interpretation of multi-cause relations and synergies. It took years before asbestos was accepted as a serious health threat, just as it took years to get acceptance that volatile organic solvents can result in brain damage among exposed workers. The latter case indeed even gained the label 'Nordic syndrome' from researchers who denied the 'evidence' presented. When including environmental concerns in the design of products, uncertainties have to be included according to the precautionary principle. In these cases, the simplistic idea of evidence-based environmental strategies turns out not to be very helpful.
3. Conferences for engineering design – often dominated by mechanical and automotive engineering – assign much attention to formalised design methods.

These methods typically build on the assumption of a linear process or at least a process in which objectives and design specifications can be defined from the outset and the design activity becomes a sequence of optimisations and choices to meet these criteria. The design problems may refer to demands from customers or users, but the assumption is that these can be translated into objectives and criteria setting the stage. Even though several surveys have demonstrated that these formalised methods and models are rarely used in industrial design practice and that actual design practices do not satisfy the assumption of linearity, engineering textbooks on design continue to present the idealised methods as if their implementation is just about to happen. Especially in cases in which several engineering disciplines are involved in the development of a new artefact with functional and user characteristics only partly understood at the start of the design project, a quite different process can be observed in which involved engineers negotiate the assignment of qualities to the artefact and its technical components – in practice constructing not only the product but also the object world that makes it useful and assigns meaning to it (Bucciarelli 1996).

4. Knowledge management has already been a shared concern among engineers and business managers for a long time, under the assumption that knowledge in practical use can be handled as packages of given and codified contents – the only problem being to convince the experts that they should support this codification and packaging process. In the business world, the contemporary and growing awareness of the importance of knowledge resources and knowledge capabilities of employees to a firm's competitiveness has given this field of management even greater emphasis. Following the definition of engineering practice domains with its experience-based heuristics and routine-based activities along with the definition of competence, the picture of knowledge as something to be stored 'in machines' instead of people and to be retrieved and combined whenever new uses appear does not work. Instead, knowledge management, despite producing awareness of the fundamental role of knowledge and cooperation, ends up supporting images of IT-based knowledge handling, which might itself produce costly procedures and conservatism in the design strategies companies actually use.

In each of these cases, some limitation to the engineering sciences involved and their claimed close relationship to approaches from the natural sciences are demonstrated by the need for including other types of knowledge coming from engineering practices as well as from the realms of social sciences.

Conflicting 'Ways Out' and New Modes of Learning

The growth of the use of technology in the latter half of the twentieth century, in combination with the large investments made in engineering research by industry as well as research institutes and universities, has resulted in tremendous growth in bodies of technological knowledge, the number of new technological domains, and specialised technical science disciplines (Wengenroth 2004). Differentiation in engineering specialties puts pressure on engineering education to cope with the diversity and to keep up with the frontline of knowledge in diverse fields.

Areas that address technology and have close affiliations with engineering represent a broad variety of subjects and approaches, including, for example, pharmaceuticals, architecture, computer science, information technology, environmental studies, biotechnology, nanotechnology, and technology management. These professional areas do not necessarily see themselves as part of engineering. In some areas, new perspectives on techno-science can create novel relationships between science and technology. Such fields as biotechnology and nanotechnology have blurred the boundaries with the natural sciences as well, leading to the creation of such fields as mathematical engineering and nanotechnology in the natural sciences.

These developments have also resulted in a growing number of new specialisations in engineering, producing tensions between generalised engineering knowledge and the specialised knowledge needed in individual domains of technology and engineering practice. Examples of these specialisations include highway engineering, shipbuilding, sanitary engineering, mining engineering, power generation and distribution engineering, offshore engineering, aeronautics, microcircuit engineering, environmental engineering, bioengineering, multimedia engineering, and wind turbine engineering. This development has been called 'expansive disintegration' (Williams 2003), reflecting the combined expansion of the number of technologies, specialties, and disciplines on the one hand, and the continued disintegration of what once may have been the unity and identity of engineering on the other.

All these specialisations led to an increase in the numbers and variety of courses focusing on technical sciences. At some technical universities (e.g. MIT and DTU), the curriculum has been organised into modules, giving students choices about how to structure their own education. While some universities expanded the number of specialisations, others coped with disciplinary congestion through renegotiation of core contents and opted for elective courses in only a limited part of the curriculum.

Some argue for general pedagogical reform based on project-oriented work to give students a broad understanding of engineering work and problem solving, with less emphasis on the theoretical knowledge represented in existing courses and disciplines (Kjersdam and Enemark 2002). In a less radical manner, many engineering schools have tried to add certain new personal skills to their requirements and curriculum, complementing teaching in the natural and technical sciences with training in communication skills, group work, and project management. These requirements are found in the ABET 2000 demands, for example, and are included in most engineering reforms, but they do not necessarily address the problems raised earlier concerning the heterogeneous character of engineering knowledge in practice.

The dominant role of technology also demands multidisciplinary approaches and challenges the science-based, rational models and problem-solving approaches. For example, in the field of environmental studies, the need for new approaches in industry based on cleaner technologies and product-chain management challenged established disciplines in sanitary engineering based on end-of-pipe technologies and chemical analysis. From treating nature as a recipient of wastes, engineers had to accept that nature itself has been dramatically affected and that environmental knowledge had to include the design of production processes and chemicals as part of what had become a continued redesign of nature. Blurring boundaries between technology and nature has introduced serious ethical and political issues into the core of engineering.

Another example can be found in the field of housing and building construction engineering. The need for integrating both social and aesthetic elements, as well as user interaction in both the project and use phases of construction, led to several attempts to overcome the traditional division between civil engineering and architecture. Educators have tried to solve this problem by combining staff from different disciplines – engineers, architects, and sociologists – hoping that solutions would emerge from the multidisciplinary melting pot. In several cases, the integration turned out to be difficult to achieve; housing construction and city planning in engineering crumbled in spite of these attempts.

Concerns about the role of technology in society have raised issues of a more fundamental nature concerning the content of engineering education and its relation to technology, exemplified with controversies about highway planning, chemicals in agriculture, nuclear power plants, and the social impacts of automation. The concerns also questioned the role of knowledge in engineering, and critics demanded a humanistic input into the curriculum with such subjects as ethics, history, philosophy, and disciplines from the social sciences (Beder 1998). This idea was based on the assumption that engineering students, through confrontation with alternate positions and opportunities to discuss social and ethical issues, would be better prepared to meet the challenges of technology. However, in many engineering education programmes, these new subjects have ended up being add-on disciplines not integrated with engineering and science subjects, contributing further to the disciplinary congestion in engineering.

The rather mixed set of response strategies applied to date demonstrates the complexity of the challenges and the different opinions among engineering schools about how to respond. None of the single solutions seem to solve the challenges alone. Neither giving science more space by reducing engineering practice nor focusing on pedagogical methods or protecting engineering science by adding social science components addresses the full complexity of the challenges.

New Approaches to Design and Disciplinary Boundaries

Changes in the role of technologies in a society where consumer uses, complex production, and infrastructures are increasingly more important have led to more focus on the integration of usability and design features. Traditional jobs in processing and production have not vanished, but new jobs in consulting, design, and marketing have been created. These new jobs demand new personal and professional competencies, and require new disciplines that contribute to the knowledge base (Sørensen 1998).

During the 1990s, several engineering schools started new lines of education emphasising engineering design skills and introducing aspects of social sciences into engineering design curricula. These additions included technology studies, user ethnographies, and market analysis. The development of new and diverse technologies also reflects the limitations of technical sciences in being able to cover all aspects of engineering (Bucciarelli 1996; Bijker 1995). Examples of these reformed engineering programmes can be found at Delft University in the Netherlands, Rensselaer Polytechnic Institute in the USA, the Technical University of Denmark, the Norwegian University of Science and Technology, and several other places.

These transformations will – if taken seriously – fundamentally challenge the role of engineering schools in the future by including much more heterogeneous engineering programmes and new perspectives on the basic divide in the sciences between the social and the material.

Another – for the time being seemingly more dominant – solution is to accept that the idea of a single unifying engineering identity has proven to be problematic and increasingly outdated. Engineering education will unavoidably become more diverse in the future. Integrating engineering into the general university structure as suggested by Williams (2003) could be a tempting solution, removing the rigid focus on core curricula while still fighting the battle for the acceptance of engineering science. However, the problems of including professional, practical knowledge and maintaining the need for professional skills in engineering are not solved by referring students to an even more diverse science base at universities. Neither does emphasising the many new science-based specialisations in engineering provide a solution, for these may pull engineering further away from the practical knowledge also needed. Their curricula are supposed to contribute to a coherent set of engineering competencies, although they have little resemblance to established domains of engineering practical problem solving and solutions.

Although engineers' identities as creators and designers are supported in both historical writing and strategic reports about the role of engineering in the future, the reality of engineering practice seems to place engineers in roles closer to analysts and scientists in laboratories and modern technical industries. Even in future-oriented reports on engineering, there is a tendency to expect problem-solving abilities in societal and environmental issues from engineering without questioning the dominant foundations of engineering curricula (NAE 2004).

New insights emerging from innovation theory, demonstrating a broader scope of innovation practices, coupled with changes in the societal use of technology that imply growing complexity and a need for social skills, point to the need for improvement in engineering education. At the same time, innovations over the past decade are leading to changes in the role of technology that may make the role of traditional engineering competencies less central in the future. Policy and management attempts to govern innovation processes have also broadened the scope and shifted the focus from technological development and breakthroughs to a broader focus on market demands, strategic issues, and the use of technologies.

The underlying assumption in most of the training given by engineering schools on engineering problem solving is that engineers are working with well-defined technical problems and methods from an existing number of engineering disciplines. This assumption does not answer the question as to whether engineers are competent in handling the social implication of complex technologies as well as the non-standardised social and technical processes in which problems are poorly defined and involve new ways of combining knowledge. Simply broadening the science base in a more interdisciplinary direction, including especially the social sciences and humanities, may not have been a satisfactory solution due to biases in these disciplines on focussing on genuine social phenomena, leaving technology and design issues as secondary objects of study.

The mere addition of topics to the curriculum does not change engineering practices or provide a better integration of knowledge. A new engineering identity will be based on the answers to these questions:

- What competencies are necessary to manage the creative, socio-technical, and design skills that need to be improved in engineering education?
- What is the meaning of engineering problem identification and problem solving today, and how can they be reflected in engineering education?

Many reforms in engineering education, including some in Denmark dating from the mid-1970s, emphasised the need for problem solving and project work that emulated real engineering practice, but these reforms did not provide the complete answer. The response lies in a new understanding of the role of science in innovation and the use of technology in context. This approach underlines the need to bridge the divide between the disciplinary knowledge of the technical and social sciences and the practical domains of engineering with their unique knowledge and routines that integrate the social, practical and technical aspects of technology at work. It is necessary to rethink disciplinary knowledge as presented in engineering education as well as to reform the content and structure of that knowledge.

In this respect, the limitations to the engineering sciences and their models become a crucial issue as does the understanding of technologies as hybrid constructs building on several both disciplinary and practice-based knowledge components. Engineering domain knowledge of technology includes often implicit assumptions about the specific use and the context of social relations and settings that is needed to make the technology functional. In contrast, communications of the technology's specifications mostly are presented in standardised and decontextualised ways. The implicit social constituencies first show when the technology is moved into new contexts that contrast the ones in which the engineering domain knowledge was constructed.

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