Engineering design competences
– controversial relations between techno-science discipline and engineering practice domains pointing to new foundations for engineering knowledge

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Studies of practical engineering design competences on one hand and the role of scientific discipline in the science based engineering curriculum as developed especially since WW2 on the other form the background for this paper. The role of engineering knowledge as produced in the context of engineering educations at large is seen as the key to understanding the dominant strategies of machination as produced and implemented in engineering practice. In contrast there is a need to bring new perspectives both to engineering design and to the understanding of engineering knowledge.

The crowding of engineering educations with an exploding number of new specialities and disciplines has made the tradition of a 'polytechnical' education as praised in the traditions of engineering education obsolete. 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 competences are blurring the hitherto so unified engineering identity.

While the introduction of social sciences and humanities primarily has functioned as an add on to the already crowded and often rather disperse engineering curriculum, new ways of understanding technologies as hybrids constructed through historical and situated actors associations has created a new ground for interdisciplinary integration. In design engineering educations these new types of knowledge has become foundational for the approach to technology.

Introduction

By the 1990s there have been raised basic questions in both the United States and Europe about the relevance of engineering education as it had developed since World War II. The problems included a lack of practical skills in modern engineering training, a mismatch between the need of industry and the science being taught, and the kind of 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 highly technically skilled cooperative workers rather than the innovative and creative engineers of technology for society. The knowledge and broad innovative capacity needed to produce creative design engineers able to cope with contemporary technological change were seen as missing in engineering education.

Several educational initiatives have addressed these issues, and attempted to outline plans to reform engineering education. Some focus on engineering curriculum or the pedagogy and learning modes employed; some develop completely new engineering programs based on new technologies. Other initiatives combine business, management, and organizational understanding with engineering, or alternatively emphasize 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). Other critics seem more confident in the achievements of engineers in society, and argue for the continuation of a traditional science-based engineering curriculum (Vincenti 1990; Auyang 2004). But they share the view that technology and the natural sciences are two distinctly separate approaches to knowledge, thereby contradicting the popular, though misleading notion that engineering science is applied science. However, they do not raise critical issues related to the social and institutional dependencies of technology. Unfortunately, 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. Also contemporary developments in the natural sciences and engineering sciences have blurred the boundaries. New approaches of techno-science seem to be gaining ground as the characterization of the ties between modern science and technology, leaving neither one in a subsidiary role (Ihde & Sellinger 2003). These new approaches recognize the role of technology as a contributor to scientific achievements, and change the basic idea of nature and technology. The question is whether these accounts are satisfactory in understanding and coping with the contemporary problems in engineering education in relation to the demands from engineering practices at large.

Two basic elements are important to understand the 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 article 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.

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 program 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.

At the outset, until the early 20th was a gap in engineering curricula between science classes based on high degrees of mathematically formalized 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.

One of the leading institutions in this change in the US was the Massachusetts Institute of Technology (MIT). Although engineers made significant contributions during the war, the success of the Manhattan Project put physicists in the spotlight, and savvy engineering leaders recognized that the path to prestige lay in engineers' closer emulation of scientists. In Europe, this orientation toward 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 toward formalization of science councils and large government-sponsored research programs, centred on the peaceful utilization of technologies developed during World War II, spurred a dramatic increase in research at technical universities, and a change in the methods of teaching engineering.

During the first half of the 20th century, polytechnic universities had to fight for acceptance. They were acknowledged for their foundations in science, but were questioned about whether they could conduct independent scientific research; or were limited to practical experiments with technical improvements and practical implementation. These controversies manifested themselves in the acceptance of doctoral studies at technical schools of higher education. In Sweden and Germany, as in many other countries, decisions about what should qualify as scientific achievement and who was qualified to judge were very controversial. The controversy ended with an acceptance of technical or engineering science as a distinct area of scientific inquiry, although the image of engineering science as merely applied natural science continued to dominate many discussions about the character and role of technical sciences.

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 & Zysman 1987; Dertouzos; Lester & Solow 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, more speed – goals that were conducive to scientific approaches (Reynolds & 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 & 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.

Whereas systems engineering of the 1950s could be narrowly analytical and hierarchically organized, new ideas of technological systems in the 1980s and 1990s focused on the relationship between technology and its social and industrial context. This new relationship and understanding of the natural and technical sciences is reflected in the notion that engineering as techno-science developed in the field of sociological studies of science and technology to reflect the new intimate relationship between these fields of science (see e.g. Juhlin & Elam 1997).

Changes in the foundation of engineering education, with the expansion of science-based technical disciplines, also has led to changes in the curriculum of traditional vocational schools of engineering, as well as funding for research. 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, practical knowledge, and skills of students who had previously worked as apprentices in construction firms, machine shops, and industry. During the 1960s, the curriculum of these technical schools was expanded, and many of their specialized lines of engineering education were extended in length and scope. Typically, these changes included improvements in mathematics and natural sciences by copying the science base from engineering universities, while attempting to maintain their practical orientation.

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 & Kammerer 1975). While this type of engineering education was well supplied by the traditional, smaller crafts-based industries, the growth in the size of industries led to a change in the ways the workforce was trained, leading to an increasingly specialized machine shop skills in the workforce. Fewer candidates had the necessary broad skills and apprenticeship training required by the engineering schools. The schools were forced to establish other recruitment systems to survive. This process resulted in a complete reversal of the basis for recruiting students during the 1990s. As a result, it is difficult today to distinguish the two different lines of engineering education from one another, both because of the convergence of their student enrolments and the nature of their educational focus.

Historical roots – from engineering practice to science discipline

The structure of many engineering institutions is still based on the big four in engineering – civil, mechanical, chemical and electrical – that originates from the 19th and early 20th century. Although engineering schools kept on training their students to solve practical industrial problems, and academic research was often difficult to distinguish from industrial consulting even after World War II, electrical engineering was the exception almost from its origins in the early 20th 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 have specific problems and industries that relate to their founding years, but as the demand for science-based research and teaching became prominent, the original roots to practice and industry lost their significance. With the changing demands, more abstract courses, and 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 generalizations. However, in the transformation process, concrete experiences and practice-based knowledge, embedded in specific technical solutions, were often 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 movement away from the engineering practice and experiences that are needed to make technology functional (Gibbons et al 1994).

Contemporary tensions in engineering education may be deeply rooted in the diversity of modern technologies. The applications of these diverse technologies throughout society require increasing differentiation in the education of engineers. This diversity has already presented new challenges to the definition of engineering competence. The diversity of technologies presents new challenges to an engineering institution's sense of unity, identity, and standardization of professional preparation. 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 educational reform and negotiations for change. And even more important, the arguments for a common basis for engineering despite all the specialties support the orientation of engineering education towards generalised science based approaches and the role of a natural science and mathematics contribution to the core of engineering studies.

Engineering domains versus discipline – theoretical reflections

Attempts to identify the demand for engineering competence can be made by focussing on the special problem definition and problem solving activities that characterises engineering work. At the outset emphasis must be put on defining the difference between scientific activities and solving engineering problems. 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 identify 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 some times 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 prioritise the relevant knowledge and emphasise knowledge produced by the natural and technical sciences as the most important for engineering, while other disciplines contributions 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 involves 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 – an assessment of the problems in question does have satisfactory solutions seen from the actors involved in the process of staging the problem solving process at large and the expectations and resources at hand. 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. While most professionals including engineers may tend to use the knowledge they command, a more careful analysis will demonstrate that it is not well defined from the outset which types of solutions are relevant and whether these exist or may need to be developed. The problem-solution relationship may be open-ended but the demand for solutions from the engineering practice is evident and the choice of methods and knowledge therefore an intrinsic part of engineering. This result in quite some freedom in the way problems and solutions are defined and demands creative input into many parts of engineering. This is not only the case in construction and design work, but also in other types of problem solving activities where results are only indirectly dependent on the employed theories and methods.

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 experienced engineers knowledge as a competence that unfolds as a repertoire of principles and routines transmitted through specific solutions and practical approaches (Ferguson 1992; see also Boshuisen & Schmidt 1992). This results in theories, methods and practices representing rather different levels of idealisation, specification and documentation.

While codified knowledge per definition 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 experienced engineers repertoire – 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, understand situations and contexts, find relevant solutions, and balance technical and non-technical demands etc. This is where the routines and heuristics become crucial for the outcome of engineering and the professional competent seem to solve problems better (see e.g. Patel et al 1991; Barley & 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 the learning processes through practice. Such framed situations of problems 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 competences involved. In recent discussions also the notion of ‘mode 2 knowledge somehow illustrates facet 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 IT, food technology, biotechnology, environmental management etc.

In contrast the codified knowledge produced and transferred in the engineering science disciplines are based on a historical process of idealisation and reduction of the objects of study involved. While their origin 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 develop into rather autonomous knowledge communities with their own – potentially dogmatic and specialised view – of the problems to be solved and developing even their own epistemic cultures (Knorr Cetina 2000). Exactly because of their boundary definition and the idealisation of the knowledge objects and models they handle they can produce objectified knowledge that can be assigned value and relevance independent of the existing messy problems as realised inside engineering practice domains.

Quite some parts of the body of knowledge and experience in engineering is as a consequence of both the role of engineering practice domains and the technical science disciplines idealised character particular and local in their reference and dependency of specific technologies and their utilisation. This is a process that continuously goes on in parallel to the production of technical sciences, standardisation procedures concerning technologies world wide and the following codification and exchange of knowledge and the attempts to overcome local delimitations and to establish a global technological knowledge.

Competence has become a significant focus in educational policy as well as industrial policy during the last ten years. While discussions concerning the design of education earlier 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. A discrepancy has developed between what is honoured as good school performance and good business performance, and this is 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 discrepancy between engineering practice domains and the disciplinary knowledge still dominating engineering education.

One of the dynamics behind the interest for competence in engineering is the on-going proliferation of the practical arenas of engineering. Technology does not only become more complex in the sense that a technological development arena comprises multiple strands of engineering specializations. 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 design educations 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, as we see it, is to create relations between production of knowledge, skills and abilities, and the practical usefulness of knowledge, skills and abilities. Focusing on competence rather than qualifications emphasizes the differences between the goals for an educational practice and the goals for a professional practice. Concern for competence clarifies 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 in themselves, 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 & Munch 2005):

- Competence is relational and contextual; i.e. it is a perspective on personal performance in a context; so in addition to assessing a person, competence also involves an organization, norms, values, instruments, aims, intentions etc.
- Competence involves the process of realization, and therefore the resources involved in realization: To create conditions and argue relevance, one must possess attitudes, motives, will power, drive, intuition, communicative skills etc.
- Competence is knowledge, skills, and abilities in a form and structure that individuals use 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.

As an example, environmental competences are not produced through separate learning processes with analytical and practical goals. The environment competence dimension is formulated within the field of study and with a given horizon and role envisioned for the persons and groups learning. Competence dimensions are always related to a field (scientific disciplines, professional environments, problem complexes, institutions etc.) that targets the competence dimension and defines its scope. Which environmental competences should engineers have, as distinguished from architects or economists? Therefore educations involving environmental competences will reflect – explicitly or implicitly – the practice and the ideals concerning the profession's actions as well as political and scientific goals and values.

Machination and the idealised 'blind' eye – examples of mismatch

As examples of The critical relations between engineering practice domains and techno-scientific discipline can be illustrated with examples taken from very different areas of engineering: wind turbine development and the role of aerodynamics, the identification of environmental objects of regulation, lifecycle methods and the problem of data complexity, formalised design methods and the role of design creativity, and knowledge management and the assumptions of knowledge in practical use.

When the recent phase of wind turbine technology development started in 1970s after the controversies about nuclear power and the use of fossil fuels many researchers and policy planners – even 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 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 still were limitations to the understanding of turbulence and non-smooth flows the 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 series of experiments and measurements of profiles of wing in wind tunnels (Vincenti 1990) were seen as a historic pathway to the now science based understanding of the design principles. But this proved to be a very wrong assumption as experts from the Boeing and NASA later concluded. Some of the most prestigious wind turbines designed based on these principles broke down after short periods of operation and did not turn out to be very energy efficient (Jørgensen & Karnøe 1994). The aerodynamic problems and the loads on the structures in wind turbines were much more critical and first decades after the first experiments started a more complete picture of the specific phenomena involved in the aerodynamic operation of wind turbine wings could be established. In a sense the difference in operational conditions were simple and striking, but not enough to raise questions about the generality of aerodynamics among the research based engineers, while the designers of wind turbines in e.g. Denmark basing their knowledge on test runs and small steps of upgrading from one design to the next took a different outset, as they considered the operational conditions of wind turbines to be characterised by extreme stress conditions from vibrations and unstable wind pressures along the wing and between them.

While the environmental sciences and also engineering to a large extend take the environment for granted as some aspects of nature especially relevant to human living conditions, the identification of environmental objects of regulation turns out to be a much more politically influenced and undetermined process where the identification of the sources of recognized pollution phenomena or health problems is a quite complex and difficult process. This becomes evident not only in relation to the science and laboratory problems of e.g. identifying a relationship between cause and effect but also in the interpretation of eventual multi-cause relations and synergies. It took years before asbestos was accepted as a serious health threat, as it took year to get acceptance for volatile organic solvents to result in brain damage among the workers exposed – in the latter case this was even called the ‘Nordic syndrome’ as several other European countries’ researchers denied the ‘evidence’ presented. In some cases also strong industrial interests are involved as in the case of leaded petrol that from the very beginning was competing with ethanol as the additive to improve the octane of petrol, but first after serious documentation of the accumulation of lead in nature a ban was decided. When environmental strategies for e.g. design of products are to be decided upon the uncertainties have to be taken into consideration to follow e.g. the precautionary principle. In these cases the simplistic idea of evidence based environmental strategies turns out not to be satisfactory.

When participating in the organised conferences for engineering design – often dominated by mechanical and automotive engineering – formalised design methods and models play an important part. These models build typically on assumptions of a linear process or at least a process where the objectives and criteria can be specified from the outset and the design activity consequently is 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 uncovered an industrial design practice where these formalised methods and models rarely are used, and where the design practice does not satisfy the linear assumption process, the engineering textbooks on design continue to present the idealised presumptuous methods as if their implementation is just in the waiting. Especially in cases where several engineering disciplines are involved in the development of new artefact with functional and user characteristics only partly understood at the start of the design project, a quite different process can be observed where the involved engineers are negotiating 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).

Knowledge management has been a shared concern among engineers and business managers already for a long period of time and the assumptions seem to be that knowledge in practical use can be handled as packages of a given and codified content – 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 the knowledge resources and capabilities of their employees for their competitiveness has even given this field of management more emphasis. Following the definition of engineering practice domains with its experience based heuristics and routine based activities and the definition of competence the picture of knowledge are something to be stores 'in machines' instead of people and to be retrieved and combined whenever new uses appear does not work. Instead knowledge management – besides producing awareness of the fundamental role of knowledge and cooperation – ends up supporting images of IT-based knowledge handling which might produce costly procedures and a certain type of conservatism in the companies design strategies.

Conflicting 'ways out' – specialisation and new modes of learning

The growth of the use of technology in the later half of the 20th century, in combination with the large investments made in engineering research by industry and by research institutes and universities, has resulted in tremendous growth in the body of technological knowledge, the number of new technological domains, and specialized technical science disciplines (Wengenroth 2004). Differentiation in engineering specialties put pressure on engineering education to cope with the diversity and to keep up with the frontline of knowledge in the diverse fields.

Areas that address technology and have close affiliations with engineering represent a broad variety of subjects and approaches, 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 of techno-science can create new relationships between science and technology. New 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 specializations in engineering. Changes in the demands for specialization created tension between generalized engineering knowledge and the specialized knowledge needed in individual domains of technology and engineering practice. Examples of these specializations include highway engineering, ship building, sanitary engineering, mining engineering, power generation and distribution engineering, offshore engineering, aeronautics, microcircuit engineering, environmental engineering, bio-engineering, 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 was the unity and identity of engineering on the other.

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

General pedagogical reform based on project-oriented work are also argued for giving students a broad understanding of engineering work and problem solving, with less emphasis on theoretical knowledge represented in the courses and disciplines (Kjersdam & Enemark 2002). In a less radical manner many engineering schools have tried to add certain new personal skills to their requirements and curriculum by complementing the natural and technical science teaching with training in communication skills, group work, and project management. These are competences that are implied in the project-oriented model and in the less demanding problem-based learning model. These requirements are found in e.g. the ABET 2000 demands and are included in most engineering reforms, but they do not necessarily address the problems raised concerning the heterogeneous character of engineering knowledge as discussed earlier.

A very different response had been to question the concept of engineering education altogether, by giving more space in the curriculum to science-based teaching, by reducing the amount of laboratory classes, and by weakening the ties to industry and the technological domains from which engineering originated.

The dominant role of technology demands multidisciplinary approaches, and challenges the science-based, rational models and problem-solving approaches. These demands have given rise to new areas of engineering education. For example, in the field of environmental studies, the need for new approaches in industry based on cleaner technologies and product chain management challenged the already established disciplines in sanitary engineering based on end-of-pipe technologies and chemical analysis. From focusing on nature as a recipient of wastes, engineers had to realize 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 re-design of nature. Blurring boundaries between technology and nature had 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. Several engineering education departments tried to solve this problem by employing 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 difficult; housing construction and city planning in engineering crumbled in spite of the attempts. This dilemma left engineering housing construction departments in situations where the focus became more theoretical rather than contributing to the design and functionality of building construction.

The decade of the 1990s was not the first time that concerns about the role of technology in society had surfaced, but this time the questions raised issues of a more fundamental nature concerning the content of engineering education and the impact on technology exemplified with controversies about highway planning, chemicals in agriculture, nuclear power plants, and the social impacts of automation. The concerns questioned the role of knowledge about technology and some 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 programs, these new subjects have ended up being add-on disciplines often not integrated with engineering and science subjects, contributing further to the disciplinary congestion in engineering.

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. The 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 emphasizing engineering design skills and introduced aspects of social sciences into the curriculum of engineering design. 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). Examples of these reformed engineering programs can be found at e.g. Delft University in the Netherlands, Rensselaer Polytechnic Institute in the U.S., 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.

New approaches to design and disciplinary boundaries

Early in the 20th 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. [36]-[13], 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 the 'adapt knowledge to new types of problems'. The focus is more often on problem solving, and less on problem identification and definition (Downey 2006). This focus emphasizes the problem of engineering identity in distinguishing between engineers as creators and designers versus analysts and scientists.

Although engineers' identity as creators and designers is supported in historical writing and in strategic reports about the role of engineering in the future, the reality of engineering practice as represented and constituted in the engineering educations seem to place engineers in roles closer to analysts and scientists in laboratories and modern technical industries. While also future-oriented reports on engineering have a tendency to expect problem solving abilities in societal and environmental issues from engineering, they most often do not give any convincing clues about how these competences can be achieved without questioning the dominant disciplinary foundations of engineering curricula (NAE 2004).

New insights coming from innovation theory, demonstrating a broader scope in innovation, 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. On the other hand, innovations during the last decade are leading to changes in the role of technology that may make the role of the traditional engineering competences 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, and the even non-standardized social and technical processes where the problems are undefined and involve new ways of combining knowledge. Simply broadening the science base in a more interdisciplinary direction, including the social sciences and humanities, may not have been a satisfactory solution due to these disciplines own bias towards 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 seem to change engineering practices or provide a better integration of knowledge. This may partly be a consequence of the disciplinary orientation of engineering education where humanities and social sciences are kept in a marginal role in relation to engineering science as well as engineering practice. A new engineering identity may though 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?

The reforms in engineering education, initiated – already from the 1970s in Denmark – in some engineering schools, emphasized the need for problem solving and project work that simulated 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 existing need to bridge the divide between the disciplinary knowledge of the technical sciences 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, and a corresponding need to reform the content and structure of that knowledge.

In this relation the limitations to engineering sciences and their models become a crucial part as does the understanding of technologies as hybrid constructs building on several both disciplinary and practice based knowledge components and embedding assumptions of use and social relations related to specific localities and historical settings even though these may become part of standardised socio-technical ensemble (Bijker 1995).

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 curriculum, 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 do the many new science-based specializations in engineering provide a solution which even may bring engineering further away from the practical knowledge also needed. As also argued earlier in this paper most technical disciplines focus on particular technical solutions taught as individual courses and with less emphasis on their application. These courses are supposed to contribute to a coherent set of engineering competencies, although they have little resemblance to an established domain of engineering practical problem solving and solutions.

The other crucial aspect for engineering technology of the future is the handling of design challenges coming from the more and more dominant social role of technology in society and for the environment. This must lead to a redefinition of what the core competences of engineering comprise. Here the understanding of the actors involved in negotiating and prioritising technological innovation become as important as the specific technical knowledge as the choice of problem-solution pairs does not point only to given ways of using technology. Also the challenges from health threats, resource depletion, and environmental loads resulting from the use of technologies demand a re-definition of the elements important to consider as the basis for engineering design processes.

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