

Challenges to Future Engineering Professionals – How to Prepare Students to Face Them

Zbigniew Prusak

Central Connecticut State University

ABSTRACT

Today's graduates acquire knowledge that will not be sufficient for a lifetime career and, in some instances, will become obsolete in a matter of just a few years. Facing the predicted 3 to 6 career changes in one's lifetime and an ever growing volume of knowledge needed, preparation of students must be a little different in the future. Should the engineering education process concentrate on teaching 'specialists' or 'generalists'? What do we know about the knowledge and skills that will define a successful engineering professional? Product Realization Skills (PRS) - knowledge and skills that form the core of presently demanded engineering competencies are described along with problems in effective teaching of PRS. The paper analyzes various skills valued by engineering and technology professionals and educators, as well as the changes in the importance of these skills. Weaknesses in preparation of engineering graduates as seen by industrial leaders and engineers from different countries are also presented.

1. INTRODUCTION

Many highly industrialized regions of the world continuously transform activities leading to generation of their economic wealth. Conversion of raw materials into useful goods as a classic definition of production is being rapidly extended by addition of various market-oriented services and activities related to transfer and utilization of information. The 'service society' or 'information society' has a growing need for people who can find the right information and use it to create (design, test, manufacture, improve, etc.) new solutions to existing or upcoming problems. Most economically developed countries realize that winning in competition is not based on a combination of low labor costs and yesterday's technologies but rather on a combination a low total cost, innovative products, high quality and responsiveness to market. To sustain such a path of economic development, education of qualified individuals becomes an issue of utmost importance. It is obvious that the days of graduating from university with knowledge that is sufficient for a lifetime are long over. Just the past decade has brought an unprecedented degree of expansion in the scope of engineering activities. New jobs which demand interdisciplinary knowledge and skills that were previously considered unrelated to engineering, are being created. The progress of technology and the rapid change in business practices transform the practice of engineering resulting in broadening of the meaning of "engineering" far beyond technical applications. The practice of engineering becomes increasingly global especially in the economically most developed countries. Already in some multinational corporations engineers in one division compete for funding of their activities with overseas divisions. The need for versatility in engineering training, continued strong accentuation of traditionally emphasized engineering knowledge base, plus skills to achieve goals in a constantly transforming business environment become therefore increasingly important. What is the knowledge and skills demanded by professional activities of the near future? How do American and overseas universities fulfill these demands now?

As the breadth and depth of engineering knowledge is already too large and too rapidly expanding to be taught in a four-year program, engineering education faces a new challenge: what universities should and can concentrate on in the process of engineering education. The issues of a 'specialist' versus a 'generalist', readily marketable skills or solid knowledge base have been debated for some time [1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13] and will be certainly coming back more often in the future. How to teach all the knowledge and skills within a 4-year undergraduate programs? A century ago, completion of a 4-year program was required to enter engineering profession and a 3-year program to enter medical profession. Nowadays, engineering still requires 4 years of university study whereas medicine more than 6 years. Unless all universities decide to do that, the extension of engineering programs beyond 4 years is presently unrealistic. Such extension will certainly be highly unpopular from the university marketing point of view because it may lead to a loss of prospective students. Therefore, some knowledge and skills may have to be left for on-the-job training or for a readily accessible lifelong training at local universities and affiliated technical and business training centers.

2. WHAT NEEDS TO BE TAUGHT AND WHAT CAN BE OMITTED

2.1. Task-oriented knowledge and skills or skills in using newest tools

Knowledge and skills required to complete mental tasks (high cognitive) and repetitive manual tasks (low cognitive) are demanded in various degrees depending on the job performed. Also important for all jobs involving creativity and solving one-of-a-kind situations is intuition (design, judgment decisions, some trouble-shooting situations, search for information, etc.). With growing experience, a person may rely more on his past practice having less need for using intuition to solve a problem. In contrast to mental and repetitive manual tasks, the intuition, which is an elementary ability of most living organisms, is yet to be understood, described and applied for use in machines. In American culture, intuition is often regarded as individual capability (a gift, a talent), but some efforts to improve it are present throughout the educational process. Open-ended problems, 'what-if' discussions following a set of solutions to a problem, brainstorming with students, are samples of the activities needed to be practiced in order to improve execution of any mental tasks. Undoubtedly, these activities help shaping intuitive capabilities (i.e. educated guess) of a future decision-maker. It is obvious that most of these activities can be performed only after a certain amount of underlying core knowledge and past practices have been acquired. Otherwise, course activities may suffer from students' loss of interest and slip into 'anything goes' situations. That type of learning activities is obviously more difficult to grade and can lead to frustration of many students who expect a clear-cut path to follow: *problem statement + initial conditions + solving techniques = answers*.

As compared to the education of engineers, education of engineering technologists is more practice-oriented. As a result, the two groups acquire different levels of theoretical and practical knowledge, and different capabilities of realizing various stages of product development (e.g. conceptual development of a new tooling, design of the tooling using a sophisticated CAD system such as ProEngineer, testing for reliability, etc.). Application oriented engineering technology programs must fulfill their goal of providing a practical knowledge which necessitates teaching various mechanical skills and software tools. However, overemphasis on teaching current tools carries a danger of university becoming more of a trade school.

The speed of changes in both engineering practices and tools used, depends largely on a discipline. In general, tools change rapidly, practices much slower and good theory and principles stay around for a long time. Many academics passionately oppose practitioners in the matter of including a programming language or a current market hit canned software to a university

curriculum [6]. They oppose to teaching a tool for the sake of mastering it just because it is widely used. Turski strongly recommends teaching universal concepts while using appropriate tools mainly to enhance practical training. Further mastering of tool related skills should be left up to interested students. Such approach to curriculum necessitates on-the-job training in specific tools and practices, but this is where the very idea of apprenticeship comes to play.

It is therefore more important to emphasize good algorithms to solve a problem rather than perfecting how to solve a problem using a particular software. For the same reason that understanding is emphasized over remembering in teaching physics and mathematics, ‘*know-how*’ must be emphasized over ‘*know-a-tool*’ in teaching engineers and engineering technologists. On the other hand, most employers are driven by short-term goals and impatiently want a new employee to be ready to produce immediately, the hottest tools sell best. Nevertheless, adjusting educational activities to comply with such requirements is not the best solution for future challenges and will leave the employee more difficult to prepare for a different task or a job. Teaching of tools is a short-term solution and must not be put before teaching of ways, past and current practices, going about unknown and resourcefulness in finding information needed. Nowhere else it is so evident as in the case of teaching computer science subjects where knowledge of tools often becomes outdated after 3 to 10 years. The process of outdated may be sometimes even faster as in the case of knowledge or skill closely related to a very big industrial hit that is rapidly superseded by somebody else’s product. Even greater danger for a skilled operator (but not for a well-educated professional) are the industry’s preferences for certain type of CAD/CAM tools. If a graduate finds a job in a field that uses software tools different from those he or she spent time honing during college years, then that time investment becomes partly questionable.

2.2. Creativity and learning from history

Engineering professionals working in highly developed countries will be required to provide innovative solutions and to create new products and services. Many even successful designers spend a great deal of time rediscovering already existing solutions. Transposing the proverb “Only fools learn from experience, smart peoples learn from history” into the engineering ground, we can say that previously devised designs, both successful and unsuccessful, form a great base for learning inventiveness. One of the important student activities, which should be included in curricula more frequently, is the forensic case studies. Such studies offer extensive possibilities of assigning small to large size projects tailored to the level of students’ knowledge, and, as such, could be used even during a freshman year. A limited use of such case studies is already present, especially in civil engineering curricula. Other engineering disciplines are equally good, if not better, grounds for introducing the study of failures. Forensic case studies provide also an additional benefit early in the academic education process. They teach historic perspective for the topic, spark students’ interest about the role of an engineer, professional ethics and expected practice standards [14]. From my experience in implementation of such activities in mechanical and manufacturing field, students like the idea of being discoverers and investigators, but must be rigorously guided during early exercises. Additional benefit of such studies is the interdisciplinary flavor of studying failures.

2.3. Non-technical knowledge

An engineering education is no longer a pathway to business leadership, as we see fewer engineers leading engineering enterprises, especially the large ones. According to data from the American Association of Engineering Societies, the U.S.A. accounts for only 12% of over one million BS degrees in engineering granted worldwide every year [15]. This number is much lower than the percentage contribution of the American economy to the world’s economy. Increasingly, a

significant number of engineering students pursues careers in traditionally non-technical fields such as business, law and health related occupations. These non-technical fields value problem solving skills, and critical and logical thinking established by a technical education. This trend in career pursuit is visible in all economically developed countries, and the United States is its most vivid example. For these engineers and technologists, an interdisciplinary education and communication skills play a very important role in their successful careers. A constant growth of interest in non-technical issues among engineering students is commonly observed and reflected in the design of engineering curricula [12, 16]. Some innovative curricula assign as much as 50-60% of required credits to be fulfilled by free or directed elective courses [13].

2.4. Knowledge ‘when-needed’ and ‘perpetual learner’

With growing volume of knowledge needed, knowing how to learn becomes an issue of utmost importance. Facing predicted 3 to 6 career changes in a lifetime, students must be taught how to learn. ‘Perpetual learner’ has already become a fact of life, especially in the most rapidly advancing industries such as: computer sciences, biotechnology, pharmacology and medicine, to name just a few. With the rapidly growing volume of accessible information, and an easier and faster access, students are already taught how to obtain discipline-specific information. However, techniques of self-organization and efficient work are not taught and are largely left up to be self-discovered by each student. To address the increasing volume of relevant knowledge, there are suggestions of reforming engineering curricula using “top-down” or “up-front” plus “as-needed” or “just-in-time” approaches to delivery of knowledge [17, 18]. Early introduction to engineering problems and learning of the basic knowledge *when needed* and *as much as needed* to solve these problems is advocated. Better problem solving skills, creativity, resourcefulness in information search and positive experiences in teamwork are the expected outcomes from introducing these approaches very early in curriculum.

3. IMPORTANCE OF SUBJECTS VIEWED BY INDUSTRY AND ACADEMIA

3.1. Product Realization Skills

A recent study conducted by ASME among senior-level managers from US industry and mechanical engineering departments at the US universities gives an interesting outlook on differences and commonalities between industry and academia [19]. It ranks most important skills and areas of knowledge mastered by BS level mechanical engineering graduates as seen by the industry and by engineering faculty. The survey results are presented in Table 1. These skills and areas of knowledge can be labeled together as Product Realization Skills (PRS) and they form the base for what I call ‘Functional Rationality’ of an engineering professional. As seen in Table 1, the high degree of agreement between industry and academia is very clear, which suggests that educators know what should be taught.

On the other hand, it is significant that two PRS valued by industry (Concurrent Engineering and Geometric Tolerancing) did not make the top 20 on the US academic list. It is also very important to point out that Concurrent Engineering and Geometric Tolerancing are among the cornerstones of Polytechnic education especially in Central Europe where design and manufacturing are not perceived as very separate disciplines the way they are in North America. One PRS not listed in academic list, Value Engineering, is an area of knowledge that is still regarded in academia as a continuous compromise search, a topic of lesser educational priority than ways to achieve a technically superior solution.

Table 1. Most important Product Realization Skills as viewed by industry and academia. Numbers in % column show percentage of industrial respondents who selected a particular skill or area of knowledge among twenty most important ones for a BS level mechanical engineer [19].

Rank by industry	Rank by academia	PRS	%
1	1	Teamwork	94
2	2	Communication	89
3	11	Design for manufacture	88
4	5	CAD systems	86
5	7	Professional ethics	85
6	3	Creative thinking	85
7	8	Design for performance	85
8	14	Design for reliability	82
9	9	Design for safety	80
10	--	Concurrent engineering	74
11	6	Sketching/drawing	74
12	12	Design to cost	74
13	19	Application of statistics	73
14	--	Reliability	73
15	--	Geometric tolerancing	71
16	--	Value engineering	70
17	4	Design reviews	68
18	10	Manufacturing processes	68
19	18	Systems perspective	67
20	20	Design for assembly	67
--	13	FEA	*
--	15	Physical testing	*
--	16	Design of experiments	*
--	17	Test equipment	*

The survey suggests also that engineering graduates continue to be only marginally competent in some PRS that are important to the product realization process driven by its life cycle. In general, main problems in effective teaching of PRS are:

- 1- many concepts are introduced late in the curriculum (during senior level courses or at the capstone projects)
- 2- too many concepts are introduced in a short period of time (do not allow students to learn and progress based on their own mistakes)
- 3- late introduction of PRS does not allow students to practice searching for unknown concepts and solutions (most senior level courses and projects are based on a concept of utilizing knowledge acquired in prerequisite courses)
- 4- over-emphasis on ability of using mathematical analysis which usually requires having initial conditions and constraints (not often the case in real-word problems)
- 5- little importance accorded to alternative (non-mathematical) ways of formulating problems and modeling, such as use of logic, words and diagrams

- 6- emphasis on optimization and avoidance of solving engineering contradictions
- 7- little significance given to understanding of non-technical drivers of engineering activity such as market demand, environmental demand etc.

Is then the American engineering education doing an inadequate job in these areas and spend too much time in the less important ones? It is tempting to say yes, but we must remember that mastering many of the skills listed in Table 1 requires experience and time consuming practice. Also, with the exception of professional ethics, teamwork and communication skills, all other PRS listed require a sound foundation in the basic engineering knowledge.

To my knowledge, a similar study to find most important PRS for graduates of Engineering Technology programs has not yet been conducted. My industrial experience suggests however that PRS that would most likely score higher on industrial list for BSMech.ET, as compared to the industrial list for BSMech.E.:

- Geometric Tolerancing
- Concurrent Engineering
- Manufacturing processes

The PRS that would most likely score lower on industrial list for BSMech.ET, are:

- Design for Performance
- Design for Reliability
- Application of statistics

3.2. Weaknesses of engineering graduates

Table 2 shows a list of twelve major weaknesses of engineering graduates and senior students in fields of mechanical, manufacturing and industrial engineering through author's international industrial experience. The list contains inputs from practicing engineers, engineering managers, owners of engineering businesses, technicians and customers (product end users). The inputs were gathered through interviews and cover the period of the mid 80's till present and come from several European countries (Poland, France, Austria, Germany, Italy, Switzerland, Finland and UK) and from Canada and the USA. Important to point out is the fact that depending on social culture and education process, some weaknesses are found to have a different degree of significance in different countries. Furthermore, some weaknesses are considered to be a somewhat normal part of the development of a young engineering professional. Despite stressing engineering and scientific knowledge base throughout curricula, certain areas of knowledge and some skills that form the very core of engineering knowledge are not taught to the satisfaction of industry (listed in Table 2 under numbers 1, 4, 5, 6, 7 and 8). As noted above, with growth of practical experience some weaknesses (mainly these numbered 4, 5 and 6 in Table 2) tend to become less apparent.

It is not surprising that the list of engineering weaknesses as seen by the US industry [20] coincides with a substantial portion of the list in Table 2. Some additional important items listed by Todd et al. are:

- technical arrogance
- poor perception of the overall engineering process
- lack of appreciation for variation
- consideration of manufacturing as boring

Although the two lists show more commonalities than differences, it is worth noticing that the list by Todd et al. does not contain some of the weaknesses listed in Table 2 (numbers 5, 7, and 12) because they were seldom considered important in the US education and social culture in general.

Table 2. Twelve major weaknesses of engineering graduates and senior students in fields of mechanical, manufacturing and industrial engineering as seen in Central and Western Europe and North America.

<ol style="list-style-type: none"> 1. Little knowledge and marginal understanding of manufacturing processes. 2. No knowledge of value engineering and little appreciation for it. 3. Glorification of Hi-Tech, complicated solutions. 4. Disrespect for effective Low-Tech solutions. 5. Belief that creation of something new is always better than improvement of something already existing. 6. Lack of design capability. 7. Avoidance of contradictions in problem solving - drive to optimize existing solutions or add Hi-Tech patches. 8. Lack of skills in defining core of a problem and deciding that a solution is ‘good enough’.. 9. Preference to work as individuals (no desire to work in teams). 10. Little project planning skills. 11. Little hands-on skills. 12. Overreliance on computer modelling and little understanding of field-testing.
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4. FUTURE ENGINEERS AND TECHNOLOGISTS: GENERALISTS OR SPECIALISTS

“Three things are required at a university: professional training, education of the whole man and research. For the university is simultaneously a professional school, a cultural center and a research institute” [4]. The trend in technical education, particularly engineering education since 1960’s, has been to concentrate on engineering sciences and to eliminate the influence of engineering practice. It becomes increasingly recognized that engineering sciences alone are not sufficient to educate a successful technical professional [11, 21, 22]. As an example, revisions of ABET requirements [2] place greater emphasis on engineering problem solving through systematic, scientific approach and through reinstatement of teaching engineering practices and interdisciplinary practices through ‘industry best practices’ that extend beyond popular ‘case studies’. Outcomes-oriented education which reflects needs of the society and the demands of industry is expected to replace activities-oriented education of the present.

Many universities and colleges adopted model of research-intensive university as a model of excellence. Such approach is not in the best interest of undergraduate students who have not yet developed basic engineering knowledge and skills. The engineers of the future will more heavily depend on broad intelligence as well as on traditional technical knowledge and skills. Universities must introduce students to the world beyond theory, equations and computers, and integrate technical skills and knowledge with the business know-how and practices. The role of engineering and technology education in the near future will require putting more weight on integration of engineering activity functions and product functions (technical, environmental, economic, financial, social, etc.). Some educators believe that a goal of engineering education should be to prepare students to function as “integrators”, believing that a designer must be able to connect inputs gathered from the appropriate specialists [9]. Others emphasize importance of teaching specialists [10], or a more halfway approach ‘specialist-first-generalist-second’ [5, 7, 8, 11, 13]. Ricoeur insists on the necessity for conveying general a culture in order to provide students with better universal

control of the techniques and specialized knowledge. This general culture is greatly needed because of growing mobility of all professionals [3, 7].

Table 3 lists competencies that engineering and technology students must develop before graduating regardless of the issue of ‘specialist versus generalist’. Some of these competencies, such as number 4, 5 and 7, were not strongly emphasized in education of previous generations of engineers.

Table 3. Important competencies of future engineers and engineering technologists.

<ol style="list-style-type: none">1- Possess engineering and scientific knowledge base.2- Task-oriented understanding of using that knowledge base.3- Ethical behavior.4- Systematic and interdisciplinary evaluation of problems.5- Team solving of problems, and organization of such activities.6- Independent action and self-organization.7- Effective communication of issues and new ideas to technical and non-technical people.8- Exploitation of the intellectual capability and knowledge base for perpetual learning and adaptation to evolving professional requirements.9- Knowledge of how to learn and how to find answers to problems.

The demand for highly trained engineers who in everyday practice use the previously mentioned interdisciplinary skills as an addition to their technical skills continues to be strong. Such type of work environment is often found in the development of ground-breaking technologies, some of which will not even find industrial applications. The traditional science and technology oriented engineering education continues to be very well suited for that type of work [23, 24, 25]. Nevertheless, team work, financial responsibilities and communication issues have already highly influenced that type of work environment [8, 25].

5. CONCLUSIONS AND RECOMMENDATIONS

Academia and industry voice many, often contradicting, opinions about suitability of theory-oriented and practice-oriented educational models. Which of the two is better suited for a first job of a graduate and his/her later career development is impossible to answer, largely due to the huge variety of professional duties assigned to engineers. Universities must therefore strike a balance between a perfect preparation of engineers and technologists for their first job (industry’s short-term demand) and education for lifetime of learning and changing demands (university’s moral obligation which coincides with industry’s long term demand). It needs to be emphasized that it is not the university’s primary responsibility to concentrate on ready-to-use skills, as it is not industry’s responsibility to teach a university graduate how to use his/her theoretical knowledge. University role is to prepare graduates for their first job as well as for dealing with new and yet unknown challenges waiting in the future. As explained earlier in the article, achieving these two goals require sometimes different academic activities.

Four most important tasks of higher education still will be:

- 1- Expanding intellectual horizon.
- 2- Providing discipline-specific knowledge base.
- 3- Teaching how to function in society.
- 4- Preparing for lifelong learning.

The purpose of higher education, its duty to students, has not changed much in the past: numbers 1, 2 and 3 from the above list. Near future will most likely not eliminate these historically established tasks and add ever-growing importance to task number 4.

The ongoing challenge for technical higher education is to determine how to provide enough knowledge and skills to ensure functioning in work environment which constantly demands more knowledge. What exactly should be taught and how? There are some advocates of 6-year undergraduate studies, but extending time spent in college is presently rather unrealistic. As the tuition costs continue rising faster than incomes, majority of students are forced to work and study, which greatly limits time they can allocate for academic development. No improvements in the matter of tuition containment are predicted for the near future. Narrower scope of technical subjects covered by American undergraduate curricula, as compared to curricula of overseas institutions, put American students in real disadvantage when compared to their European or East Asian counterparts. Adapting the teaching process to the needs of the future work environment by putting more emphasis on industrial practice and time-efficient learning will therefore become increasingly important.

Since universities have no control over requirements of present and future business environment, educating future engineers and technologists will require a frequent adaptation of curriculum, ways of delivering knowledge and acquiring practical experience. It will be necessary to pursue many long-term endeavors in a well-structured manner in order to deliver good and up to date education. Some of the most important long-term endeavors to be pursued are:

- 1- Identification of primary employers and industries hiring school's graduates and following development of the graduates' careers later on.
- 2- Determination of needs of university customers (incoming freshman and transfer students, local and national industry, global industry).
- 3- Increase in student exchange between universities from different countries.
- 4- Periodical revision of curricula to identify areas of knowledge and skills currently taught, level of competency achieved versus required, skills that are outdated and skills that are not taught but are required in practice.
- 5- Development of more flexible curricula (especially for junior and senior years) which allow for a greater freedom in choosing elective courses in pursuit of student's individual objectives.
- 6- Introduction of a university-industry cooperative learning early in the curriculum (freshman or sophomore).
- 7- Development of a well structured industrial apprenticeship for engineering students as an integral part of mandatory portion of the curriculum (e.g. 2 semesters spent working in the industry, preferably at two different places).

It is clear that striking a good match between the best designed curriculum and the needs of all possible jobs the graduates may hold is simply impossible. Therefore, education of an engineer should be primarily a formation of a capable, open-minded and creative person equipped with the discipline-related functional knowledge. The above described academic and practical activities should foster the desired outcomes of the professional development of engineers and technologists.

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BIOGRAPHICAL INFORMATION

ZBIGNIEW PRUSAK is an Assistant Professor in the Engineering Technology Department at the Central Connecticut State University. He teaches a broad range of courses in Mechanical, Manufacturing and Industrial Systems programs. He has over 10 years of international industrial and research experience in the fields of precision manufacturing, mechanical systems and metrology. E-mail: prusakz@ccsu.ctstateu.edu