Learning Engineering Problem Solving in Different Learning Environments

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**ABSTRACT:** Professional engineering problems are manifold in nature and learning to solve them is a difficult task. All learning situations compass, in addition to the substance, also physical, social and cultural environments and are affected by many stakeholders. Student understanding of engineering problems and learning EPS can be enhanced by taking into account the whole learning environment's effect on him or her. This will be increasingly important in the future, when the profile of engineering shifts even more to interdisciplinary direction and the engineering students are more diverse group than ever.

1. **INTRODUCTION**

Both 'engineering problem solving' and 'learning environment' are concepts that are understood in many ways. Engineering problem solving, hereafter referred as EPS, can be thought as anything from all activities related to engineer's work problems to a certain sequence of actions taken to solve a very specific type of problem. In between the extremes lies indefinite number of definitions. Situation is very similar with the concept of learning environment. A broad definition can take the whole world to be one's learning environment. On the other hand the rapid growth and diversification of the electronic study and co-operation environments, has reserved the term to the use of the debate in their area. Thus in many occasions the term learning environment is used only in referring to this software and the activities it supports.

In this paper we use relatively broad definitions of both. EPS, as we understand it, is the way engineer goes about solving professional problems. Professionality of a problem is defined through practice. Thus it is not just the nature of the problem but also the circumstances and surroundings which can make a problem professional to engineer. For example the extent of conservation of wetland is not necessary an engineering problem by nature but it may become one, or at least part of one, if the wetland happens to situate in possible future plant site.

We define also the concept of learning environment in a fairly wide manner. Our view is focused on the area where most of the undergraduate learning takes place: formal education. Students' actions are guided by their conceptions of various factors related to learning and becoming professional engineer. Many of these factors can be included in the analysis of learning situation by looking at also other stakeholders and activities together with the social and cultural conditions they sustain, instead of focusing at only the teacher student relationship.

The research on the learning environment of engineering education and EPS, presented in this paper, is carried out as part of the engineering education anticipation and development project FuturEng at the Finnish Association of Graduate Engineers TEK. The objective of the FuturEng project is to find out what are the challenges of the Finnish engineering education in the new
knowledge-intensive economy, Learning Society, up to 2015. In addition to the research project on the learning environment, several other subprojects are included in the project e.g. evolutionary futures research on the challenges of engineering education in Finland up to 2015, research on the labour market follow-up and feedback systems and women in engineering.

All the most important stakeholders of engineering education are included in the FuturEng-project. These stakeholders are not willing only to passively follow what is happening to engineering education in Finland, Europe and globally. All stakeholders are participating in the interactive research process to create common understanding of desired, possible and threatening future scenarios on engineering education in order to influence the future engineering education.

2. DIMENSIONS OF PROFESSIONAL ENGINEERING PROBLEMS

Engineering problems is a very complex set of problems. Their properties vary along many dimensions. A thorough analysis of the dimensions is not possible within the framework of this paper, but to show the diversity and to provide ground for learning environment analysis, we are going to discuss some dimensions of engineering problems, illustrated also in picture 1.

2.1. Problem definition

Problems entering engineer's desk have sometimes one, sometimes several possible solutions i.e. they can be closed or open. For engineer the openness or closedness of the problem usually depends on the decisions and procedures problem has gone through before reaching engineer: defining the size of a reactor can be considered to be a closed problem if someone else has already decided on the reactors material, shape, production rate and so on. Most engineering problems are open by nature and require estimating, evaluating and making choices. Text-book problems are, however, mostly closed problems with one definite answer. Students often know this and thus their quest becomes 'finding the answer' rather than 'solving the problem'.

2.2. Ethics and values

The dimension of values varies a lot in real-life EPS. Closed mathematical problems will have the same solution regardless of the person solving them and thus can be considered to be totally value-free. In the other end of the spectrum are the problems that require plenty of creativity and decision making, like many broad design problems. According to Lindgren (1998) the ethical questions related to engineering can be roughly divided to three categories: first the global 'questions of conscience' like nuclear power and population growth, second the general questions regarding the risks and responsibilities related to all technologies and third the questions related to engineers own perspective and work tasks.

Clift (1998) describes the shift in engineering problems by talking about Mark I, Mark II and Mark III engineers. The industrial revolution gave birth to the Mark I engineers, whose "decisions were based on choosing the 'best' technology using available materials and energy to optimise economic returns". Along the 20th century the role of the engineer gradually shifted to Mark II engineer "who saw his primary role as supplying human needs". As our society today is more technology dependent than ever, and Mark I and II engineers' techno-centric approach is not sufficient enough to support the public decision-making a Mark III engineer is called for. She "will need to take on the new role of representing the implications of technological choices in public deliberation, as an impartial expert rather than as an advocate of his or her preferred option". (Ibid.). Change is evident in the dimension of values as traditional objectives of economicality and efficiency are being accompanied by environmental, ethical and societal objectives.

2.3. Applicability of solutions

Whether an engineer is looking for a general or local solution is a matter of circumstances. When solving local problems, different heuristics and rules of thumb are widely used. In that type of EPS it is essential to know what kind of heuristics to use and how. Finding general solutions is
more science-like activity. General solutions - theories, models or heuristics - have to be based on scientific theories and scientifically justified assumptions. Finding general and local solutions are often competing activities. Finding a general solution requires usually lot resources whereas local solution is the optimal solution regarding also the expenses. Finding a local solution for general problem is not sufficient and finding a general solution to local problem is usually too expensive.

2.4. Nature of the process
EPS processes can be analytic or synthetic. Especially the highly technical analyses resemble the analytical practices of natural science and the analyses with human emphasis (e.g. usability) are often quite similar to processes in social sciences. In engineering work the synthetical processes accompany closely the analytic ones and can actually be considered more important. Engineering typically involves 'putting things together' to form different kinds of entities (products, production processes, systems, procedures etc.). Although analysis is often identified with research and synthesis with design, this is not the standpoint we have taken here. Rather we see both research and design as processes, which consist of a set of problems of both kinds.

Hendricks et al. (2000) studied the epistemology, methodology and ontology of engineering science and reached a conclusion that engineering sciences differ in respects from both pure and applied natural sciences. As epistemology of engineering and the theory of design are yet to be constructed and the natural sciences play a remarkable role in engineering education, it is easy for engineering students to acquire a positivistic worldview typical to natural sciences. This may hinder them from seeing the differences in research and design and produce frustration when "the right answer" is not found. Learning to understand the nature of EPS is an important phase in learning efficient EPS. Unfortunately this step is often forgotten in teaching EPS.

2.5. Need for previous knowledge
Sometimes engineer comes across with problems that require no previous knowledge but only logical reasoning. However, most of the engineering tasks demand significant amounts of propositional (factual), procedural (methodological) and tacit knowledge. Tacit knowledge consists of two dimensions: technical and cognitive (Nonaka & Takeuchi 1995, 8). Technical tacit knowledge is also known as 'know-how'. Cognitive tacit knowledge reflects our implicit models of world and the future and thus shapes our perception of the world. (Ibid.) The process and success of EPS is very much dependent on the amount and type of previous knowledge the engineer has.

2.6. Object work versus social work
Bucciarelli and Kuhn (1997, see Adelman (1998, 39)) state that EPS happens in both 'object world' and 'social world'. The object world is about the properties of task related physical phenomena. The social world is brought in by the customer. Object world comprises scientific constraints and sets the physical limits to solutions. Customer poses engineer different kinds of constraints like the ones related to time, cost or quality. Physical constraints are not negotiable but the social ones often are, thus they are dealt differently with. Adelman (1997, 38-39) stresses the social aspects of engineering and states that "the best engineering solutions fit the culture in which they are applied" and that "design problems exist because there is a "customer""

3. WAYS TO TEACH ENGINEERING PROBLEM SOLVING
There are several ways to teach EPS. We present here briefly three methods, which are present in Finnish engineering learning environments.

3.1. Sequential procedures for learning individual EPS
Step-by-step methods of how to proceed in solving a problem are commonly presented when students are taught to solve text-book problems. These problems are typically closed, value-neutral and general. They have to be analysed and mathematically solved with taking in count only the physical constraints and using only theoretical previous knowledge. A typical sequence would be:
(1) draw, (2) write general equations, (3) evolve operational equations, (4) get an answer, (5) evaluate, (Venable 1997). In Finland the steps are not taught explicitly as a paradigm for EPS, but rather illustrated to students via examples and solutions to the homework problems. Although good in helping the students to get a grasp of routine calculations, sequential methods touch only a very narrow sector of engineering problems. As text-book problems are usually solved alone, the social factors of EPS don't show themselves at all as they are not included in problems either.

3.2. Problem-based learning

Problem-based learning (PBL) was originally developed for teaching medicine, but has been applied also in teaching engineering. In PBL a group of students is usually given an open problem, which they then start analysing together, before everyone goes out to do an independent inquiry. After inquiry period students come together and share their knowledge and ideas and evaluate their learning. According to the ideas of PBL the problems should resemble professional problems as closely as possible. During the process students will notice that their values and preferences have an effect in the process of analysis, inquiry and solution formulation. Solutions are usually local. Students use their previous knowledge, but one of the aims of the method is to teach them to search for information. They may use very different methods of inquiry all of which give students different kind of knowledge (propositional, procedural and tacit). Problem solving is a social process and problems contain also social constraints.

3.3. Project work

Design is often taught as project work. Projects are usually done in teams and the design problem is often authentic coming from the industry. Thus project work is one form of learning by working. From customers point of view students form an engineering team, which is expected to take into account also the needs of the customer. The pedagogical model, which explains perhaps the best learning in these situations is the Kolb's model of experiential learning a.k.a. Kolb's cycle. Experiential learning emphasises the role of meta-cognition, i.e. observing, understanding and regulating our own actions, in learning. In design teaching the emphasis in meta-cognition leads to better explication of tacit knowledge and understanding of the nature and use of heuristics.

4. HOW CAN LEARNING ENVIRONMENTS SUPPORT THE LEARNING OF EPS?

Our framework for learning environment is presented in picture 2. The four constituents and the relations between the individual and the environment were introduced by Ropo (1996). Also the different stakeholders have been taken into the framework. The most important stakeholders outside the students and the teachers from our perspective are the student communities, the industry and commerce sector, which is the biggest employer of engineers in Finland, and the academic and professional communities. Student unions and quilds have strong traditions and many activities, which effect the formation of students' social and cultural environments. Close cooperation between industry and university is also typical of Finnish system. Finnish graduated engineers have on average 20 months discipline relevant working experience (Muhonen 2000). Working while studying makes web-based courses, evening lectures and self-studying attractive for many altering thus traditional physical class-room environments. The share of engineering degrees of all tertiary level degrees is about 23%, which is the second highest share in OECD countries (TEK 2002, 11). The intake of new students has doubled during 1990-2000 (ibid, 12) and lectures of five hundred students are nowadays reality. Profession and scientific community are the main builders of the engineering image, which is also a factor influencing students' actions. The stakeholders affect students through substance (curriculum) and physical, cultural and social environments. The possibilities of the four parts of learning environment to support learning are discussed here with more detail.
4.1. Effect of substance

EPS relates to the substance taught in several ways. Substance can include the theory of EPS like solving problems with sequential methods, examples of problems and their solving, knowledge required to solve typical problems (theories, formulas, heuristics) and of course problems for students to work on. Theory helps students to become more efficient in solving routine problems, examples illustrate the variety of problems and expert ways of solving them, including some of the tacit knowledge of the solver. Working on problems develops the metacognitive skills and gives students more confidence. Knowledge-base can include all three forms of knowledge. Propositional knowledge of theories, physical, economical and legal constraints and case-information helps students to define and analyse problems. Procedural knowledge of heuristics use and limitations, and research techniques gives students tools to formulate alternative solutions and evaluate them. Tacit knowledge is more difficult to include in substance, but can partly be explicated with the use of metaphors and analogies (Nonaka & Takeuchi 1995, 13), which the teacher can include in the substance.

4.2. Effect of physical environment

Gruke et al. (2001) did a study on the effects of physical environment on engineering team performance. They concluded that environments can encourage students to work together and thus enhance the performance of the team. According to them dislocated resources encourage students to work in isolation and complete the work by putting individually made parts together, which hardly is what is meant by genuine teamwork producing collaborative knowledge building. They also state that physical environments that support collaboration also "communicate to students that teamwork is a valued part of their learning culture" (ibid.).

Another thing shaping strongly the physical environments of learning is the web-based distance teaching. DaSilva (1999) looks at the distance learning from campus student's viewpoint and notices one potential benefit in the web-based courses with both campus and remote students participating. In his words the "Remote students often have several years of experience in fields related to the discipline and are usually more attuned to practical issues. If we are able to harness this diversity of backgrounds and settings into a cohesive learning community, there is the potential for a much richer learning experiences for all." Hereby the possibility for the exchange of tacit knowledge is created.

4.3. Effect of social environment

Right kind of social environments can prepare the student to analyse problems from different perspectives, communicate with different stakeholders, manage the teams, learn from the experts (apprenticeship learning) and basically get familiar with the 'social world' of engineering practice. As engineers often are accused of being able to talk only to other engineers, engineering students should participate in social environments with students and people from other disciplines. With professions growing societal responsibility the Clift's (1998) Mark III engineer should also be familiar with expressing the central issues of her work to the laymen. Social environment in academic community is different from the one in enterprises. Getting familiar with the genuine environments in which the professional problems are solved is also part of the EPS learning process. Not only the solution that counts but also the way others are informed and understand it.

4.4. Effect of cultural environment

Not everybody thinks the same about engineering or about world for that matter. Though the 'object world' maybe same for all the engineers regardless of their cultural background, the 'social world' is definitely not. Culture defines not only the code of conduct but also the values set for the EPS. Values can sometimes be very different even in cultures that may appear rather similar. Lucena and Downey (2001) illustrate these differences in their course 'Engineering Cultures', and introduce e.g. the effects of western individualism and Japanese group identity in engineering.
order to efficiently solve engineering problems in multicultural teams or for multicultural customers, engineers have to be aware of the cultural differences in their thinking.

Engineering in general is a very male dominant culture. Jansson (1998, 80) sees three main lines of argumentation in the discussion of getting more women to engineering. First viewpoint is that women are a talent reserve to use when education is lacking men. Secondly women should have equal opportunities to choose their profession also in the area of engineering and natural sciences. Third line of reasoning doesn't see women as a presumed talent reserve but rather as a presumed competence resource, which enhances the development of technology and science. These three approaches are based on very different cultural ideas of the relationship between men, women and engineering. First assumes that men are more suitable for engineering, but that women can be used in 'case of an emergency'. Second sees engineering as women's right but doesn't take a stand on women's suitability for engineering. Third sees women as different, but equally important actors in engineering and its development.

Cultural environments during studies have a big effect on the values and attitudes the future engineer adopts. If students think that the only way to solve engineering problems is the one of white, western male they are not very likely to be successful in EPS in multicultural teams or with female customers. Diversity of social environments enhances also the diversity of cultural environments but equally important is to make the cultural differences visible by discussing about them and their reasons.

5. FACTORS AFFECTING THE LEARNING ENVIRONMENTS IN FUTURE

Diversity of the student backgrounds is expected to increase in future. Engineering students are no longer of mainly same sex, age group, nationality and labour market experience. This is due to many reasons. Firstly, more women are entering the engineering career. While the current share of women in engineering in Finland is 20 – 25 %, the share is expected to be 35 – 40 % in 2015 (Yrjänheikki 2002). Interdisciplinary skills are increasingly valued as a criterion of the quality of engineering education. A good engineer knows how to combine and apply different areas of technology and take into account the social aspect (Korhonen 1997, 66). As a result, interdisciplinary programs are increasing in engineering and they will attract in more women.

In a society, where skills and competence is the most important factor of production, learning becomes a key activity of all age groups. (Yrjänheikki 2002). Education is no longer a pipe that you enter around the age of 5 - 7 and graduate at the age of 24 – 26. Learning is an activity that has to be carried throughout one’s lifetime. Part of the learning is degree-oriented education, while other formal continuing education and non-formal education, learning at work, are important as well. This will show also in the varying labour market experience of entering engineering students. The aim of the European Union is to increase the mobility of students in Europe through the so called Bologna process. The willingness of the engineering students to study in another European country is increasing (ibid.). Engineering is studied more and more in multicultural teams.

Development of the information and communication technology has changed and will change the learning environment in engineering education significantly in future. Estimations are presented that in year 2015 it is possible to carry out 30 – 50 % of engineering studies in a virtual learning environment without a need to be present at the campus area. Although practical training already is an essential part of engineering education in Finland year 2002, it is expected that in 2015 it is even more common for enterprises to form a significant part of engineering learning environment. This is especially the case in polytechnics, where the studies are more practical-oriented than in engineering programs offered by universities. (ibid.).
6. CONCLUSIONS

Problem solving is the core activity of professional engineering work. It is a manifold activity, which at the same time deals with the laws of natural sciences and with the needs of customers and society. Developing both the 'object' and the 'social' side of EPS requires support from the whole learning environment. Students have to be provided with adequate knowledge-base in both propositional and procedural knowledge related to EPS. They have to be shown the importance of physical environment in working process and taught how to apply it in their work. Social processes in EPS and social factors and constraints in problem analysis have to be demonstrated by putting the students situations that resemble real life. Cultural factors of engineering must be made visible and students should be given experiences and examples of different cultural approaches to same problems. Physical, social and cultural environments are in key position in sharing the tacit knowledge of engineering with the students. As all the four constituents are always present in teaching and education, it is educators' important task to analyse them in different learning situations and design education is such a way that the whole learning environment supports the learning process. In the future the diversity of the student background will increase further. Engineering students will no longer be of mainly same sex, age group, nationality and labour market experience. Moreover, the virtual learning environments offer new opportunities and pose new challenges that need to be dealt with when developing the future EPS.

References:

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Picture 1. Dimensions of professional engineering problems

Picture 2. Framework for learning environments in Finnish higher engineering education