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ENGINEERING EDUCATION – IS PROBLEMBASED OR PROJECT-BASED LEARNING THE ANSWER?

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Abstract

The dominant pedagogy for engineering education still remains "chalk and talk", despite the large body of education research that demonstrates its ineffectiveness. In recent years, the engineering profession and the bodies responsible for accrediting engineering programs have called for change. This paper discusses the application of problem-based and project-based learning to engineering education, examines the difference between them. It reviews some examples of where they have been used to date and discusses the effectiveness and relevance of each method for engineering education.

INTRODUCTION

The modern engineering profession deals constantly with uncertainty, with incomplete data and competing (often conflicting) demands from clients, governments, environmental groups and the general public. It requires skills in human relations as well as technical competence. Whilst trying to incorporate more "human" skills into their knowledge base and professional practice, today's engineers must also cope with continual technological and organisational change in the workplace. In addition they must cope with the commercial realities of industrial practice in the modern world, as well as the legal consequences of every professional decision they make.

Despite these challenges, the predominant model of engineering education remains similar to that practiced in the 1950's - "chalk and talk", with large classes and single-discipline, lecture-based delivery the norm, particularly in the early years of study. Developments in student-centred learning such as problem-based and project-based learning have so far had relatively little impact on mainstream engineering education. This paper begins by examining the critical issues for engineering education and their impact on accreditation requirements. It then looks at the nature of both problem-based and project-based learning, discusses their differences and reviews examples of their application in engineering education.

CURRENT PRACTICE AND CRITICAL ISSUES FOR ENGINEERING EDUCATION

In recent years studies have been conducted in many countries to determine the technical and personal abilities required of engineers by today's industry (e.g. [1], [2]). These studies have indicated some key concerns. Today's engineering graduates need to have strong communication and teamwork skills, but they don't. They need to have a broader perspective of the issues that concern their profession such as social, environmental and economic issues, but they haven't. Finally, they are graduating with good knowledge of fundamental engineering science and computer literacy, but they don't know how to apply that in practice.

These studies have informed reviews of engineering education conducted in several countries [3], [4] and have had a major influence on the revision of national accreditation criteria for engineering programs in countries such as the USA [5], UK [6] and Australia [7]. The new accreditation approach shifts emphasis away from "what is being taught" to "what is being learned" [8]. Engineering programs are now required to demonstrate that their graduates are achieving a set of specified learning outcomes, and the means of demonstrating this is left to each university to decide and implement. There are also some requirements in each country for increased management education, design education and industry relevance of programs.

If the industry studies, accreditation criteria and reviews of engineering education are examined it is clear that the profession, the industry employers and the students themselves are calling for significant changes to the current philosophy and delivery of engineering education. What are the critical issues that need to be addressed? These can be summarised as follows:

1. Engineering curricula are too focussed on engineering science and technical courses without providing sufficient integration of these topics or relating them to industrial practice. Programs are content driven.
2. Current programs do not provide sufficient design experiences to students.
3. Graduates still lack communication skills and teamwork experience and programs need to incorporate more opportunities for students to develop these.
4. Programs need to develop more awareness amongst students of the social, environmental, economic and legal issues that are part of the reality of modern engineering practice.
5. Existing faculty lack practical experience, hence are not able to adequately relate theory to practice or provide design experiences. Present promotion systems reward research activities and not practical experience or teaching expertise.
6. The existing teaching and learning strategies or culture in engineering programs is outdated and needs to become more student-centred.

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The solutions generally proposed to overcome most of these issues involve a fundamental redesign of the curriculum in engineering programs. Revised course accreditation criteria through ABET, SARTOR and the IE Aust. will mean that all engineering institutions in the USA, UK and Australia will need to develop revised program and course structures, and teaching methods, to help their graduates to acquire the industry desired skills and qualities in the future. Most institutions will probably choose to "nibble" gradually at the edges of their existing programs, constrained by financial considerations, tradition and the expertise and experience of their existing faculty. Others may adopt a more radical approach by shifting the fundamental basis of their education approach to a project- or problem-based learning model. But why use problem-based learning in Engineering? The answer to this question is fairly straightforward. If we examine the six critical issues for engineering education proposed above, then problem-based learning is a strategy that can be used to directly address numbers 1 to 4 and 6, and for it to be successfully introduced then issue no. 5 must also be dealt with. However, there are other student-centred teaching strategies that could also address these issues, so what is particularly relevant or useful about problem-based learning?

PROBLEM - BASED LEARNING IN ENGINEERING EDUCATION

Problem-based learning has been used for professional training in medicine since the 1960's and is now used extensively in that field. It has also been implemented in related health professions. It has been suggested by many as a solution to the engineering education issues discussed above, and has been implemented to a limited extent in some engineering programs.

Design is one of the fundamental processes and activities in engineering (and basically all other engineering activities relate to it e.g. implementation or construction of designs or processes and maintenance of facilities or products). The strategy for teaching design as has been practiced in engineering programs for many years (although as stated in critical issue no. 2, not to a sufficient extent) has many similarities with the problem-based learning strategy. These have been summarised by Williams & Williams [9] as follows:

- Both have a large number of phases or stages through which to pass during the project or problem.
- Both start with an identified problem or situation which directs the students' area or context of study.
- Student initiated research is relied upon for the student to progress through the project as well as for their own learning.
- Both require high levels of student initiative, students need to develop motivation and organisation skills.
- Both lend themselves to long-term projects, PBL may be used over a short time frame but this does not detract from its ability to be used effectively over a longer time frame, as is usually associated with technology projects.
- Both are open ended with regard to outcomes, allowing the student the

opportunity to choose, after appropriate research an outcome that interests them.

- Observational skills are identified as having a high priority, especially in the initial stages during identification of the problem.
- Student reflection is an important aspect of both models, the student is encouraged to evaluate fully the outcome they have achieved.
- Both rely upon group work. (p. 361).

Hence it would appear to be a logical extension of design education in engineering to implement problem-based learning.

Existing applications of problem-based learning in engineering

The use of problem-based learning in engineering programs has been reported by several authors, although the practice is still far from widespread. One of the more well known applications has been by Don Woods in the Chemical Engineering program at McMaster University. It has been described in several publications, e.g. [10], [11]. With a strong tradition of problem-based learning already developed in medicine at the same university, the department of Chemical Engineering decided to implement it in their program in the early 1980's. The problem-based learning approach as implemented in chemical engineering is used in two courses only, one at sophomore level, and the other in a senior design project course. It is carried out in class sizes of 20 to 45 with one faculty member, (rather than tutorial groups of 5 students per tutor as used in medicine), so in the engineering course, the students work in groups of 5 but with no tutor. To make this work successfully, McMaster uses a "Problem Solving Program" (see [11] for a complete discussion of this), a series of workshops that have been embedded into four of the chemical engineering courses spread through the years of the program. These workshops help students to develop problem-solving, interpersonal skills and team skills which enable them to undertake the self-directed problem-based learning process in tutorless groups successfully. Hence the McMaster program in Chemical Engineering actually incorporates several student-centred teaching strategies and curriculum developments integrated across its program, of which problem-based learning is one component.

At Monash University, Australia, problem-based learning has been introduced to several courses in the civil engineering degree through the initiative of Roger Hadgraft. He has incorporated problem-based learning into second year computing and surveying [12]; a third year course in Systems Engineering and a post-graduate course in Surface Water Modelling [13]; and a fourth year course in Civil Engineering Computer Applications [14].

Some of the other applications of problem-based learning in engineering that have been reported include courses in:

- Hydraulic Engineering in junior/senior level at Pennsylvania State University [15];
- Design in second year Mechatronic Engineering at Curtin University, Western Australia [16];
- Water and Wastewater Engineering in fourth year Civil Engineering at

Griffith University, Queensland [17].

In all of these cases the implementation of problem-based learning has been to individual courses within a traditional engineering program, sometimes only one course due to the interest of the faculty who teaches it, sometimes in a series of courses such as Woods at McMaster and Hadgraft at Monash, but again this is usually dependent on the interest and enthusiasm of an individual or small group of faculty. For problem-based learning to be introduced throughout a typical engineering degree, it would require interest, cooperation and integration of faculty from at least the engineering, mathematics, science and business/management divisions of an institution. This is probably where one of the largest obstacles to full-scale PBL in engineering lies.

Does problem-based learning work in engineering?

Within the engineering examples of problem-based learning, the evaluations that have been undertaken have been almost entirely along the lines of student interviews or responses to open-ended questions (e.g. [14]). This qualitative research has generally found students in favour of the courses, where they have been sufficiently prepared for the problem-based environment (at McMaster and in some of the Monash courses). There have been positive program evaluations of the McMaster Problem solving program in engineering [11], but "the role of PBL in attaining these outcomes could not be easily determined because the programs studied involved multifaceted skill development efforts" [18].

Considering a broader perspective of the question "does problem-based learning work in engineering?", it is clear from the application of problem-based learning in engineering to date, that there appear to be obstacles to its implementation across a whole engineering program. This issue may relate to the nature of engineering knowledge and practice compared with medicine, where problem-based learning has been widely adopted. Feletti [19] has touched on this issue when he described "another genre of professions…where problematic topics or situations loosely define the subject matter and where professional practice is typically not the process of solving well-defined problems" (p. 146).

A very relevant and recent discussion on the suitability of problem-based learning for engineering has been published by Perrenet, Bouhuijs & Smits [20]. They conclude that "PBL has certain limitations, which make it less suitable as an overall strategy for engineering education" (p. 345). One of these is the constructivist philosophy behind PBL. Engineers must be able to apply concepts that they learn during their education at university to solve problems outside of the experience they had in the course, since every problem they encounter in practice will usually be different from those they have encountered previously in practice and almost certainly different from any they encountered at university. Perrenet et al (2000, p. 349) report that "findings from research on misconceptions suggest that PBL may not always lead to constructing the 'right' knowledge." Hence it may or may not be useful for engineering education with regard to "the acquisition of knowledge that can be retrieved and used in a professional setting".

Skill in metacognition is also essential for successful learning in PBL environments. However, this skill may not be enough in engineering due to the nature of the knowledge domain. In PBL, the order in which topics are learned is partly defined by the students themselves and hence some topics may be overlooked. Perrenet et al [20] describe the medical knowledge domain as having a "rather encyclopaedic structure, so the order in which various concepts are encountered is not prescribed and further learning will hardly be affected by missing a topic" (p. 350), (in other words, if a topic is missed now, it can be filled in later). By contrast, mathematics, physics and much of engineering have a hierarchical knowledge structure. Many topics must be learned in a certain order, because missing essential parts will result in failure to learn later concepts. This problem will be hard for a student to correct, no matter how good their metacognitive skills, because they probably can not fully compensate for missed topics as a result of using a PBL method. The issue of the particular hierarchical knowledge structure of much of engineering is possibly the most fundamental obstacle for implementation of problem-based engineering through an entire engineering program, as opposed to within individual courses in the program.

Professional problem-solving skills in engineering require the ability to reach a solution using data that is usually incomplete, whilst attempting to satisfy demands from clients, government and the general public that will usually be in conflict, minimising the impacts of any solution on the social and physical environment and doing all this for the least cost possible. Problem solutions may also extend over long time periods. Problem solving in medicine differs in that, there will only be one diagnosis (or solution) that proves to be correct, and it will usually be made relatively quickly. Treatments after diagnosis may vary, but will generally be selected from a range of well-defined options. Hence a PBL approach may be insufficient for the acquisition of professional problem-solving skills in engineering due to the usual time scale of the problems and the range of activities that they include.

One other issue raised by Perrenet et al [20] relates to the culture of the engineering profession. Although some engineers (particularly the few women!) are working hard to change it, engineering as a profession, including the engineering education sector remains a male-dominated, conservative, technically focussed culture. Hence the adoption of innovative educational methods may be difficult to implement in engineering, due to faculty resistance. Despite the fact that the medical profession could be similarly characterised (although not quite so male-dominated as it was), PBL has been readily adopted in medical education, probably because it "seems to mirror the professional behaviour of a physician more closely than the professional behaviour of an engineer" (p. 352).

It seems therefore that problem-based learning may be a partial answer for resolving the critical issues of engineering education, primarily to demonstrate the application context in early stages of an engineering curriculum. However, other active learning, student centred methods may be more appropriate and acceptable for engineering education. In particular, an approach that more closely "mirrors" the professional behaviour of an engineer could be successful. This is the basis of project-based learning.

PROJECT-BASED LEARNING IN ENGINEERING

What is it and how is it different to problem-based learning?

The term "project" is universally used in engineering practice as a "unit of work", usually defined on the basis of the client. Almost every task undertaken in professional practice by an engineer will be in relation to a project. Projects will have varying time scales. A project such as the construction of a large dam or power station may take several years, whilst other engineers may be involved on numerous small projects for various clients at any given time. Projects will have varying complexity, but all will relate in some way to the fundamental theories and techniques of an engineer's discipline specialisation. Small projects may only involve one area of engineering specialisation, but larger projects will be multi-disciplinary, not only involving engineers from different specialisations, but other professional and non-professional personnel and teams. Successful completion of projects in practice requires the integration of all areas of an engineer's undergraduate training.

Project-based learning may be defined in various ways by different educational disciplines and levels. Projects are frequently used in K-12 education, so it is a concept and teaching method that is familiar to most students. Many of the outcomes are not dissimilar to learning outcomes claimed for problem-based learning. A comparison of problem-based and project-based learning at tertiary level was made by Perrenet et al [20]. They noted that the similarities between the two strategies are that they are both based on self-direction and collaboration, and that they both have a multi-disciplinary orientation. The differences that they noted included:

- Project tasks are closer to professional reality and therefore take a longer period of time than problem-based learning problems (which may extend over only a single session, a week or a few weeks).
- Project work is more directed to the *application* of knowledge, whereas problem-based learning is more directed to the *acquisition* of knowledge.
- Project-based learning is usually accompanied by subject courses (eg maths, physics etc. in engineering), whereas problem-based learning is not.
- Management of time and resources by the students as well as task and role differentiation is very important in project-based learning.
- Self-direction is stronger in project work, compared with problem-based learning, since the learning process is less directed by the problem. (p. 348)

Project-based learning may also be applied in individual courses or throughout a curriculum as described by Heitmann [21], who differentiates between "project-oriented studies" and "project-organised curriculum" (p. 127). According to Heitmann, project-oriented study involves the use of small projects within individual courses, progressing to a final year project course. The projects will usually be combined with traditional teaching methods within the same course. They focus on the application, and possibly the integration of previously acquired knowledge. Projects may be carried out as individuals or in small groups. Project-organised curricula use projects as the structuring principle of the entire curriculum, with subjectoriented courses eliminated or reduced to a minimum and related to a certain project. Students work in small groups with a project team of teachers who are advisers and consultants. Projects are undertaken throughout the length of the course and vary in duration from a few weeks up to a whole year. In reality in engineering, a completely project-organised curricula does not yet exist, and the closest are programs where projects and project-related courses make up 75% of the program, as at Aalborg University in Denmark.

Examples of project-based learning in engineering

There are several examples of project-based learning being used in individual or a few courses in engineering programs that have been reported in the literature. Some of them use the term project-based, others use the term "problem-based learning", but are actually project-based learning in accordance with the definitions discussed earlier. Still others use the terms interchangeably, which points to the grey area that exists in engineering between these terms. The courses reported cover a range of discipline areas and program levels. Examples include:

- Final semester undergraduate industry projects in all disciplines at the Engineering College at Hogskolen i Telemark, Norway [22].
- Projects in the EPICS courses in first and second year at the Colorado School of Mines, USA [23].
- Several US examples cited in Rosenbaum [24] including Rose-Hulman Institute of Technology, Carnegie Mellon and Worcester Polytechnic Institute.

The number of engineering schools that have programs which approach Heitmann's definition of a predominantly project-organised curricula are considerably less. Heitmann cites several European examples: Aalborg and Roskilde in Denmark; Bremen, TU Berlin, Dortmund and Oldenburg in Germany, Delft and Wageningen in Netherlands (p. 124). Australian examples include Monash University and Central Queensland University. Whilst there are other universities in Australia that are now moving in this direction, these examples have been chosen since they have been well documented and in the case of CQU, successfully re-accredited since the full-scale introduction of the program.

AALBORG UNIVERSITY

The project-centred engineering program at Aalborg University commenced with the formation of the university in 1974. All engineering programs undertake a common, first year basic studies program in mathematics, physics and computer science, which is taught primarily in a traditional format. This year also includes an introduction to the methods of project work and teamwork that the students will need for the rest of their program. In the remaining two or 4 years (for Bachelor or Master's degrees), the curriculum consists of 50% project work, 25% course work (i.e. lectures, seminars, laboratory exercises) that support the project work, and the remaining 25% coursework in fundamental studies such as mathematics, physics etc.

Project-based teaching at Aalborg is strongly problem-oriented, and the projects are often practical industry problems, with new problems assigned to groups each year. Students work in groups of 5-7 for the project work, and each student group has assigned office space. Students choose a project from a list that the faculty has approved and all of a given semester's projects have a common theme of study. Each project group is assigned two faculty advisers. Faculty members will supervise three to five project groups as well as teaching coursework in their specialty area.

Anette Kolmos, a faculty member at Aalborg, points out that "What one institution practises as problem-based learning may look very much like what another institution practices as project work" [25]. However, she argues that the "ideas of problem-based learning and project work support each other and emphasize different aspects of learning" and that the main idea of both is to emphasise learning instead of teaching. Kolmos classifies three types of project work in the Aalborg program; assignment projects, subject projects and problem projects. The three types of projects deal with different objectives and lead to different knowledge and skills, but all have the common characteristic that a problem has to be analyzed and solved by means of different kinds of methods. All types also have the same phases of preparation, problem analysis, demarcation, problem solving, conclusion and reporting (p. 142). The difference between the project types is the extent of teacher control or student direction. The "problem projects" will be most like problem-based learning with regard to student direction of learning and the role of the teacher. However, Kolmos differentiates between the teaching roles as a "process-oriented supervisor" in problem-based learning compared with a "product-oriented supervisor" in project-based learning (p. 147).

Several evaluations of the Aalborg University project-based engineering program have been carried out. Some of these are described in detail in [26] and [27]. The electronic and electrical engineering programs at both Aalborg University and the Danish Technological University (with a traditional program) were evaluated by an international committee in 1998. The evaluation used self-evaluation reports from each institution, a questionnaire to graduates of each school and interviews with representatives from industry leaders, as well as a site visit to each school. The findings were that both programs were excellent but the graduates

focussed on different skills. Aalborg graduates were stronger in team skills, communication, ability to carry out a total project and generally more adaptable and thus, more directly employable on graduation. DTU graduates were stronger in engineering fundamentals and more capable of independent work, but will generally require more on-the-job training. Differences in the retention rates and completion times between Aalborg and DTU have been noted. The Aalborg dropout rate is 20-25% and most occur in the first year. In the traditionally taught Danish programs the dropout rate is approximately 40% [28].

MONASH UNIVERSITY

As discussed previously, Monash University had implemented problem-based learning in several courses within its civil engineering program. In 1996/7 the civil engineering department made a commitment to introduce project-based and problem-based learning throughout its program. The new curriculum has been phased in from 1998 (first year) to 2001 (fourth year). Monash has used the terms project-assisted learning, project-based learning and problem-based learning to describe the stages through which its students progress during the program [29]. The definitions they have adopted are:

- Project-assisted learning - Project and exercises. The teacher delivers and controls the content.
- Project-based learning - The project is the dominant activity. Students access content when required, but the teacher prepares much of it.
- Problem-based learning - Students control the content, delivery and interaction (in groups) while the lecturer usually determines the project/problem.

In the first year of the course the emphasis is on project-assisted learning, i.e. collaborative, group-based projects, but this is only in the one Civil Engineering subject. The remainder of the program in first year involves generic skill development courses, common to all engineering programs, in mathematics, computing, physics etc. The second year of the program still includes some generic skill courses, but a significant proportion of the courses are civil engineering based. These courses continue to use project-assisted learning, but with increasing emphasis on the students finding the information they require. Project-based learning is the model at third year level. In the final year of the program, students are expected to operate with significant autonomy in terms of setting projects and finding resources. Student groups are expected to identify their learning needs and find learning resources, thus this stage incorporates problem-based learning. In some subjects students work on individual projects and others in groups.

CENTRAL QUEENSLAND UNIVERSITY

Central Queensland University (CQU) introduced a project-based engineering degree in 1998. It has been described by Wolfs et al [30]. CQU offers engineering degrees in the specialisation areas of civil, electrical, mechanical and computer systems engineering. All of these programs have adopted a project-based model, with 50% of the students' workload in each semester allocated to a project-based unit. Each semester consists of two six-unit courses, used to develop the theoretical knowledge bases, and a twelve-unit project based course. The projects gradually increase in length and difficulty throughout the program. An added difference in the CQU program is that it is a co-operative format, where students undertake two semesters of a total 9 semesters in a full-time industrial work placement. In contrast to Aalborg and Monash, CQU has introduced project-based courses as 50% of first year as well. These first year courses focus on developing skills in team-work, communication, computing, problem-solving and others, as well as introducing students to engineering issues such as ethics, environmental and social factors. Initial indications are that retention rates have improved along with student grades. Program assessments have again been focussed on student evaluations.

Is project-based learning successful in engineering?

Apart from Aalborg and some other European examples, the use of project-based learning as a major part of the curriculum is new to engineering, whilst the use of the "assignment projects" or "project assisted learning" is long-standing but poorly evaluated. The most appropriate answer to this question is probably the same as that to the question of problem-based learning's effectiveness in medicine – "It depends what you want!". From the limited evaluations to date, the findings are similar to PBL in medicine. Students who participate in project-based learning are generally motivated by it and demonstrate better teamwork and communication skills. They have a better understanding of the application of their knowledge in practice and the complexities of other issues involved in professional practice. However, they may have a less rigorous understanding of engineering fundamentals.

The revised curriculum at Monash University had its first graduates at the end of 2001. A qualitative and quantitative survey of second to fourth year students in the degree has recently been conducted [31]. It was noted that "the aims of the new curriculum are taking time to be implemented" and that "learning in the department tends to be mainly project-assisted and partly project-based, rather than problem-based". Some of the positive aspects noted by students were the use of real world applications and the development of technical and problem-solving skills. The aspects that students perceived to be negative about the project-based learning curriculum were the high time demands of projects and problems with members of groups who did not pull their weight. The recommendations for continuing progress towards the intended project-based curriculum primarily revolved around continued training for both students and staff in the skills needed to make project-based or problem-based learning effective, such as teamwork and problem-solving, as well as continued education for staff in implementation and assessment methodologies that are more attuned to problem- and project-based learning philosophies.

Lecturers may also wish to evaluate the effectiveness of project-based learning implemented within their own teaching, even if that is only a single course in a program that is not generally project-based as a whole. There are various frameworks for curriculum evaluation from the education literature that may be useful in this context. One framework that was found to be readily applicable to the engineering context is based on the intended, implemented, perceived and achieved curriculum. This was used by the first author in evaluating the effectiveness of project-based learning in a structural engineering course [32].

CONCLUSION

In the context of the requirements of revised accreditation criteria and the calls from industry on what they need from engineering graduates, it would appear that these demands are unlikely to be satisfied by a traditional engineering curriculum and "chalk and talk" pedagogy. A mixed-mode approach as successfully adopted at several of the institutions examined in this review, with some traditionally taught courses, particularly in the early years, mixed with some project-based components and with the project-based components increasing in extent, complexity and student autonomy in later years of the program, appears to be the best way to satisfy industry needs, without sacrificing knowledge of engineering fundamentals. It has also been demonstrated that the engineering profession and academics are more familiar with the concepts of projects in their professional practice, than with the concepts of problem-based learning. It therefore seems that project-based learning is likely to be more readily adopted and adapted by university engineering programs than problem-based learning. The use of project-based learning as a key component of engineering programs should be promulgated as widely as possible, because it is certainly clear that any improvement to the existing lecture-centric programs that dominate engineering would be welcomed by students, industry and accreditors alike.

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