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Published in:
Educate for the future: PBL, Sustainability and Digitalisation 2020

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

A Problem-Based Approach to Teaching a Course in Engineering Mechanics

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"I never teach my pupils, I only attempt to provide the conditions in which they can learn."
Albert Einstein

Abstract

Problem-Based Learning (PBL) can be defined as a learning environment where problems drive the learning. A teaching session begins with a problem to be solved, in such a way that students need to gain new knowledge before they can solve the problem. This paper discusses the application of PBL to teaching an introductory course in engineering mechanics at Aalborg University, Copenhagen, Denmark for first semester students enrolled in the program "Sustainable Design". We pose realistic problems which do not necessarily have a single correct solution. Project work in groups also presents itself as a supplement for conventional engineering education. The students themselves should interpret the problem posed, gather needed information, identify possible solutions, evaluate options and present conclusions. The paper also presents an initial assessment of the experiences gained from implementing PBL in the course. We conclude with a discussion of some issues in implementing PBL in engineering and mathematics courses.

Keywords: PBL, engineering mechanics, engineering mathematics, interdisciplinary

Type of contribution: PBL best practice

1 What is Problem-Based Learning?

In contrast to a traditional teacher-centred pedagogy, PBL is a learner-centred educational method, based on realistic problems encountered in the real world. These problems act as a stimulus for learning, integrating and organizing learned information in ways that will ensure its application to new, future problems. However, a point worth noting here is that a problem might not always be something practical that needs to be fixed; it could also be something that initiates the learning process for instance a description of a natural phenomenon (Graaff 2016). Dahl (2018) furthermore describes theoretical problems in PBL and she perceives these as anomalies in our understanding, explanations and theories about the world. PBL is based on a constructivist theoretical framework that is also applied in instructional models such as ""Inquiry-Based Learning" (IBL).

The term Problem-Based Learning was coined in 1969 when McMaster University in Canada introduced PBL into its medical school in an effort to provide a multidisciplinary approach to medical education and to promote problem solving to its graduates (Barrows & Tamblyn, 1980). PBL was soon adopted by many universities worldwide (Mills *et al.*, 2003). Educators and researchers are still showing increasing interest in PBL approaches that claim to stimulate the students' self-learning and to promote their communication skills. In a PBL teaching situation, problems are introduced at the beginning of the teaching unit, e.g. a lesson or a semester, before presenting the students with the relevant knowledge during the course. By actively engaging with the problem, students can develop skills around identifying the information they need and also the possible sources of that information. The goal is to enable them to relate what they are learning in class to their own experiences as well as to important issues in their world (Askhave *et al.,* 2015). Nowadays, internet technology brings with it a rapid explosion of easily accessible knowledge. Graduates are expected to be critical thinkers, problem solvers and systematic in their approach and possess lifelong learning skills. The interdisciplinary nature of real-life problems means that students need to be able to integrate knowledge and skills from several disciplines as well as have personal and communication skills to be an effective group member. "The knowledge which is valued in problem-based learning is that which can be used in context, rather than that which justifies the structure of particular disciplines" (Boud & Feletti, 2013, p. 16).

In PBL, an important task of the teacher is to initiate discussions in the class in order to enhance the students reasoning skills and encourage them to apply their previous experiences to a novel case, thus enabling them to identify areas of gaps in their knowledge and prepare them to new knowledge acquisition. Through PBL, students are gradually given more and more responsibility for their own learning and become increasingly independent of the teacher in their understanding (Barrows & Tamblyn, 1980). One should also note that PBL is not merely preparing problems for the students to solve in the class, "but also about creating opportunities for the students to construct knowledge through effective interactions and collaborative inquiry" (Tan, 2003, p. 22).

Instructional, fact-based learning may continue to be important for becoming an expert at anything. In fact, using fact-based videos from websites like YouTube and Kahn Academy would make it easy for instructors to flip their classrooms by allowing students to digest instructional content at their own time and pace. This can be a genuine opportunity for instructors since it frees up class time to offer a PBL approach and personalized coaching to students as they work on projects in the class

It should be emphasized that PBL is not to be confused with Project-Based Learning, even though both learning environments are similar in strategies. Project-based learning is a teaching method in which students acquire and apply knowledge and skills by working for an extended period of time to investigate and respond to an authentic and complex question or problem that is too large to be solved single-handed (Barge, 2010). Both problem-based and project-based learning are student-centred and "emphasize the learning process instead of the teaching process" (Kolmos, 1996).

This article shows one way to implement PBL in an engineering mechanics course, where mathematics, engineering science and communication skills are taught in an integrated fashion, using a course project that deals with the solution of real-world problems and serves as a learning context. However, no claim is made that PBL would generally work in every engineering or science discipline. In fact, the suitability of PBL for engineering is still subject to debate among educational researchers. For example, Perrenet *et al.* (2000, p. 349) reported that "findings from research on misconceptions suggest that PBL may not always lead to constructing the right knowledge", given that PBL is a constructivist theory of learning.

Moreover, as Mills *et al.* (2003) pointed out, one of the obstacles to full implementation of PBL in engineering "would require interest, cooperation and integration of faculty from at least the engineering, mathematics, science and business/management divisions of an institution." Another important issue in a PBL implementation across a whole engineering program is related to the hierarchical knowledge structure of mathematics and engineering compared with medicine, where PBL has been widely adopted (Feletti, 1993). This is perhaps the most fundamental hindrance for implementation of PBL through an entire engineering program, as opposed to within individual courses in the program. Constructivist methods, where students inquire problem/situations and assign a facilitator role to the teacher, can be quite challenging, and sometimes difficult, to implement. Maybe this could be one of the reasons why many teachers may either ignore the methods or, at best, pay lip service to them. In fact, many studies revealed that teachers and educational practitioners, who are mainly interested in the improvement of teaching, are quite sceptical and are not interested in theorization (Verstappen, 1991). This entitles that new energy and resources are needed in order to narrow the gap between the theory and practice in education.

2 The Course Project

The curriculum of “Sustainable Design" includes both semester projects and courses (Aalborg University, 2015), where the courses should presumably support the projects by providing the necessary engineering knowledge that could prove relevant in the semester projects. The course “Models, Mechanics and Materials" itself should include an introduction to statics and strength of materials as well as mathematical topics such as differential equations and linear algebra (Aalborg University, 2017). As PBL teachers, it is our responsibility to design teaching situations that provide guidance to tackle authentic situations and facilitate students’ learning, in such a manner that the topics of the course are embedded within these teaching situations. The course project is therefore structured in a such a way that the fundamental topics in statics, strength of materials and engineering mathematics are covered, as required by the curriculum of the course. The textbook by Hibbeler (2019) is used throughout the course, together with hand-written notes, which are made accessible on Aalborg University learning platform, *Moodle*. The project in the course consists of three parts:

- Analysis and redesign of a swing (Figure 1).
- Analysis and redesign of a chandelier hanging from a ceiling (Figure 2).
- Modelling of a spring horse (Figure 3).

These parts are deliberately chosen in such a way that

- they are *related* to the first semester project of “Sustainable Design", where the students should design (or redesign) equipment for a playground for children. The students’ designs should meet safety requirements and should include design calculations, and
- all the central topics of the course are represented in the questions asked in the project formulation.

Figure 1: The first part of the project

Figure 2: The second part

Figure 3: The third part

The project formulation is made accessible for the students in the very first lecture, where we gave an overview of the topics of the course. Each topic in the project was then introduced into the course lectures, such that as each major content of the course syllabus was covered, the students were asked to work in groups to complete the corresponding parts of the project. Each group had to submit progress reports periodically. This was useful in providing feedback to the students before they uploaded their final project reports to Moodle at the end of the semester.

A close look at the structure of the “Sustainable Design" program will reveal that product design constitutes a major part of it. The product designer is a problem solver who, given a problem or a need, applies such fields as physics, mathematics, hydraulics, electronics, metallurgy, strength of materials, dynamics, magnetism and acoustics in order to find a solution, namely, the new product (Tayal, 2013).

One aspect of product design is related to the modelling of a real-life design through simplified physical models that can be analysed using the fundamental engineering concepts, such as those in this introductory course in engineering mechanics. This aspect of modelling is rarely illustrated in engineering textbooks developed for such introductory courses, despite its importance. Although these textbooks contain at the end of each chapter plenty of problems that reinforce the concepts covered in the chapter, they usually do not discuss the relationships with the other topics covered elsewhere in the textbook. The course project can thus be regarded as an attempt to revitalize the modelling aspect in design and to illustrate the links between all the fundamental concepts of the course that perhaps can lead to a better understanding of the big picture. We, PBL teachers, have an important educational mission: To enable the students to apply seemingly isolated, theoretical results to genuine, real problems they did not meet before. This is where, we believe, “understanding" a method or an equation comes to an end. Only in that case, the “mission is accomplished". In our course, we always began the lectures with unstructured discussions of issues related to the course project. The students were then given comprehensive introductions to the topic(s) of the day and guided through a set of sample calculations on existing designs, as well be shown in the following section.

3 A Teaching Situation in Statics: An Example

To illustrate how we apply PBL in the course, a teaching situation in statics will be presented here. As mentioned in section 1, an important educational task of the instructor is the facilitation of class discussions in a PBL teaching situation. Thus, in introducing the topic “Statics", the starting point was the "girl on the swing" project (Figure 1). The class discussions were triggered by the question “what are the conditions to be satisfied so that the girl will be sitting still and does not move?" The “no force" condition emerged clearly from these discussions. The discussions then turned on the importance of giving “directions" to the forces exerted on the girl. This personalized knowledge about forces and equilibrium is transformed to a formal, precise knowledge by going through topics such as vectors, forces, free-body diagrams (FBD) and the conditions for equilibrium (Hibbeler, 2019):

$$\Sigma \vec{F}=0 \quad \text{and} \quad \Sigma \vec{M}_0 = 0$$

As an illustration of the principles of statics, a sample problem was worked out in details in the class (Figure 4)

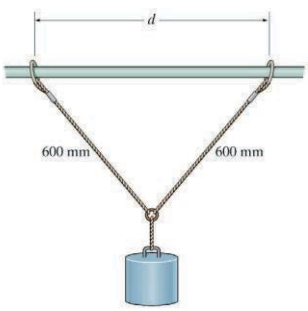

Figure 4: The example used to introduce statics

The problem was chosen to be “statistically" similar to the questions in the course project. The calculations and explanations were written with a stylus pen on a Wacom tablet (Figure 5), the purpose of which was to free the students from writing or taking pictures of the board, as the document was uploaded om Moodle at the end of the lesson. In a PBL situation, it is important to give the students time to reflect on the methods used and to ask questions, rather than spend time taking notes from the board. This strategy is used thoroughly in the course lectures and in project-related explanations. Similar teaching situations were prepared in the other topics of the course, namely, basic introductions to strength of materials and engineering mathematics.

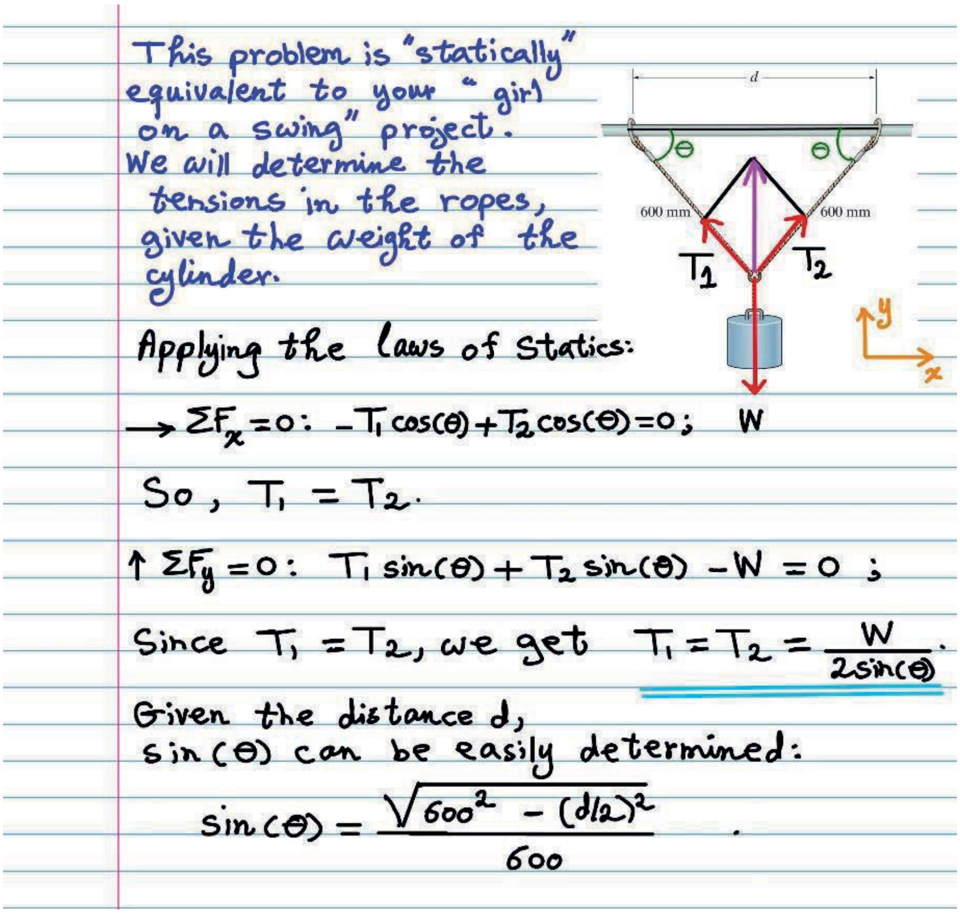

Figure 5: Solution of the sample example

It may seem that this explicit transmission of knowledge, through worked examples, contradicts the essence of PBL, where "knowledge should be constructed" and “not conveyed”. In fact, as Klahr (2009) points out, what some researchers call “direct instruction” is, in fact, very close to what good constructivist pedagogy recommends (p. 297). “Even the most zealous constructivist would acknowledge that there exist combinations of time, place, topic, learner, and context, when it is optimal to simply tell students something, or to show them something, or to give them explicit instruction about something” (p. 291). According to Rosenshine (2009), direct instruction does not mean teaching by direct transmission, but refers broadly to a teacher-guided effective teaching, including revision to find out about the students’ prior knowledge before the teaching of new knowledge, updated lesson plans, opportunities for the students to apply new knowledge and giving students constructive feedback and continuous revision. Direct instruction thus does not necessarily imply that students are devoid of opportunities for active participation. It is therefore a misconception, in “constructivist” theories of education, that teachers should never tell students anything directly but, instead, should always allow them to construct knowledge for themselves. This perspective confuses a theory of pedagogy (teaching) with a theory of knowing (Rosenshine, 2009, p. 11).

4 Examples of Students’ Solutions

In this section, excerpts of the students’ solutions of the course project are shown. Again, the raison d’être of the course project is to integrate different domains of knowledge and communication skills so that the students become able to tackle realistic problems. It is a **work in progress** in the course, since it consists of gradual stages through which the students should go through during the project. Each project group made observations and measurements in the initial stages of the project. The three parts of the project were open-ended regarding the outcomes, and thus, gave the students the freedom to choose an outcome that interests them. For example, some work groups came up with different materials for the cords holding the girl on the swing; others changed the design of the chandelier in the second part of the project so that it had two bars instead of three. According to the project formulation, the students should justify their conclusions and argue for their chosen designs. Given that student reflection is an important aspect in a PBL teaching situation, the students are therefore required to fully evaluate the results they have reached. The figures below show excerpts of students’ solutions of some parts of the project.

The lectures on matrices and linear equations were integrated in a major part of the course, namely, strength of materials. The course project is thus designed to make a connection between linear algebra and the rest of the course, e.g., in the project part “analysis and redesign of a chandelier hanging from a ceiling”, a connection is made between the mathematical statement "two equations in three unknowns" and the fact that "the middle cord is redundant". The culmination of this part was to make students reach the conclusion that a consistent system of three linear equations in three unknowns corresponds to the fact that the three forces in the chords could be determined, and thus to enable them to “see" linear algebra in action. Differential equations are also taught in the context of strength of materials, specifically in lectures on the deflection of beams, to reveal its importance as well as to provide the students with some real-life applications, that are relevant to the program "Sustainable Design".

Figure 6: The forces acting on the girl

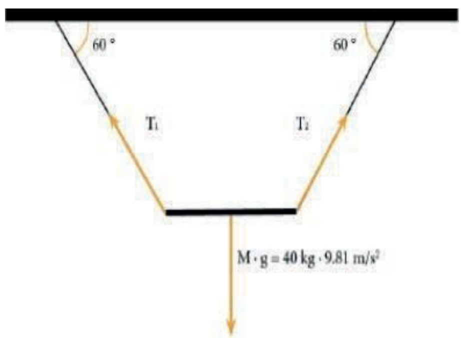

Figure 7: An FBD of the girl

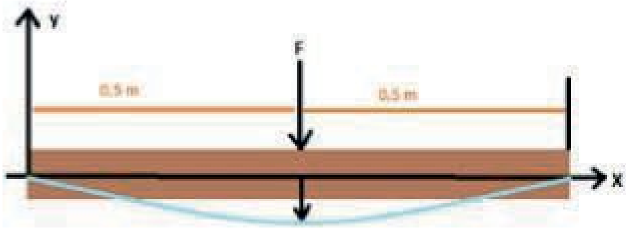

Figure 8: The deflection of the beam

$$E \cdot I \cdot \frac{d^2v}{dx^2} = M(x) \quad (1)$$

$$E \cdot I \cdot \frac{dv}{dx} = V(x) \quad (2)$$

Figure 9: Differential equations

Figure 10: Students measuring the deflection of the spring

5 Course Evaluation

The course evaluation is used to provide the instructor and the study board with knowledge of the learning outcomes of the course, in order to continuously improve it and to provide the students with suitable conditions for learning. Implementation of PBL in the course was performed in the Autumn semester 2017 and again in the Autumn semester 2018. A preliminary assessment of this implementation of PBL in the course was made through a survey of the students at the end of the semester. The students' evaluation of the course as well as their comments are made available for the instructor at the course homepage on Moodle. A comparison of student evaluations in the years 2015-2018 is shown in Figure 13.

It was observed that the students' perception of the course was improved considerably, compared with the previous surveys in the years 2015 and 2016. The course then was very teacher-driven and solely consisted of a series of lectures on the course topics, with no project involved or connection to the first semester project. Regarding the relevance of the course, most students agreed that the course project provided a practical illustration of real-life applications of the various fundamental topics covered in the course.

The students felt, however, that they needed more guidance in completing the project. This can be quite challenging to achieve for the instructor, since a balance between the amount of guidance given to the students and the freedom that should be allowed for creativity in an open-ended problem is not easy to find. The introduction of the PBL also changed the interaction and the relation between the instructor and the students quite significantly: The instructor assumed the rules of a project supervisor and a “visiting" group member, in addition to the usual rule as a lecturer. By participating in the group discussions, the instructor gained much insight into how the students tackled the problem, where genuine ideas are shaped and where students fell victims of flaws in their arguments. In fact, this was the most interesting part of the job as a lecturer! The learning environment after the revision was much more focused on the needs of the students, rather than on the strict adherence to the course schedule. This required some flexibility on the instructor's part in responding spontaneously to the project-related problems surfacing during the unstructured discussions and in adjusting the pace of the lecture to the progress made in the course project. In future offerings of the course, some adjustments to the schedule will have to be made.

It is expected that the planning on which specific subjects to cover in the lectures and which ones to move to independent learning through the course project will require some adjustments. Regarding group formation, letting the students determine the composition of the project groups entirely on their own based on friendships and working relationships from the semester project turned out to be, more or less, an adequate choice. Based on this procedure, many groups were formed through mutual agreement of all the members while some other groups essentially consisted of those students who, for some reason or another, were unable to form alliances. While it is rather clear that equal teams with culturally diversity and similarly distributed talent would be desirable, it is much less obvious how such a balanced distribution could be achieved. A group selection by the instructor would not necessarily result in equally strong teams since other qualifications such as previous leadership skills are as important for the group success as are analytic abilities and factual knowledge. Incompatibility due to work schedules and personality conflicts might also turn out as further impediments to the feasibility of the selection by the instructor. Therefore, during the next offering of the course, a random procedure, possibly with some minor adjustments by the instructor, will be adopted. It remains to be seen if such procedure will turn out to befruitful.

Another challenge associated with team-based educational activities is the evaluation of both the individual contributions and achieved skill levels of the group members. Sometimes, student groups tend to cover for under-performing members. In that regard, anonymous questionnaires judging the contributions of all team members, had to be filled out by every student. In cases of obvious extreme discrepancies in the level of contributions, different course grades were assigned for individual students in the group. An analysis of student performance in the oral exams, which were designed to be of similar level of difficulty before and after the implementation of PBL, showed a measurable improvement of the students, grades, especially in the “what if" questions, posed during the exam.

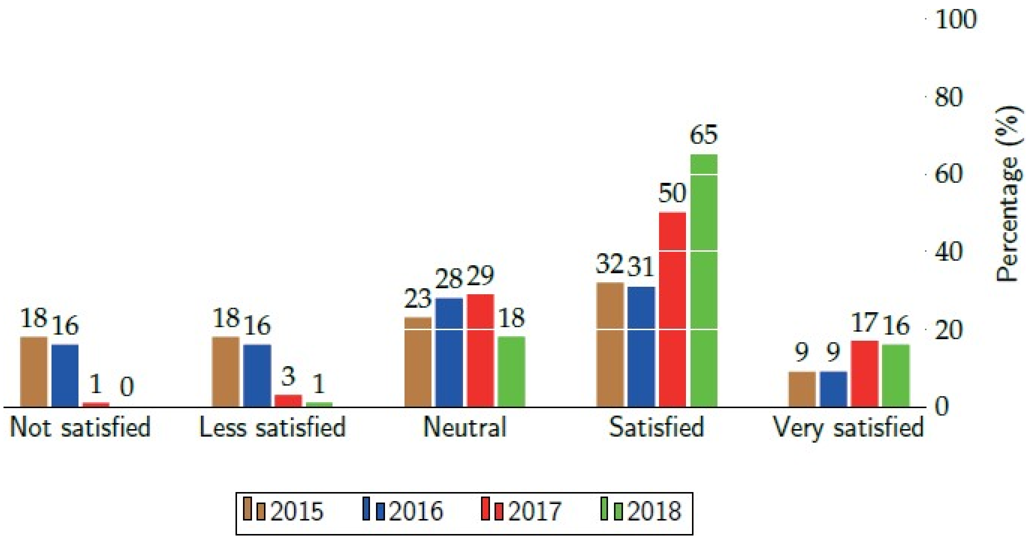

Figure 11: Comparison of student evaluations

6 Discussion and Conclusion

PBL can be successful in design-oriented engineering programs where product design plays a dominant role since "Designing is a many-sided and wide-range activity" (Pahl *et al*., 2013, p. 27), that is interdisciplinary in nature. This is exactly what we tried to achieve in the course project: To help the students overcoming what appears to them as being disconnected subjects. It seems therefore that PBL may be a partial answer for resolving a critical issue of engineering education, namely the *application context* of the courses given in early stages of an engineering program.

It is generally acknowledged that design is one of the fundamental processes and activities in engineering. The strategy for teaching design, as has been practiced in engineering programs for many years (Dym *et al*., 2005) shares many similarities with PBL. These similarities have been noted by Williams *et al.* (1994):

- Both methods start with open-ended problems or realistic situations.
- Students' progress in the project is dependent on their own learning.
- Students need to develop motivation and organization skills.
- Both PBL and teaching design have several gradual stages through which to pass in order to acquire new knowledge.
- Observational skills are equally important for both PBL and teaching design, especially in the initial stages of the problem or project.
- Student reflection is an important aspect of both methods.
- Both methods rely on group work.

Hence it would appear that the implementation of PBL is a *logical extension* of the program "Sustainable Design", as both design and PBL are analogous in their approaches. "Design projects play a vital role in providing students with a crucial attribute desired by industry for a newly graduated engineer: The ability to identify and define a problem, develop and evaluate alternative solutions and develop one or more designs to solve the problem. It is generally agreed that this attribute can only be developed by exposing students to the experience of open-ended problem solving which includes linking engineering science knowledge to complex, real-life design problems." (Schjær-Jacobsen *et al.,* 2012, p. 79).

We believe that our experience in implementing PBL in the course strengthens the argument that topics like engineering mechanics and mathematics in design-oriented engineering programs should be taught in a design context, through well-structured teaching situations that allow students to work with real-life problems that they consider beneficial to the society. In fact, solving problems of the society and the environment may be the reason why the students chose the program "Sustainable Design" in the first place.

The preparation time allocated to the course was not enough to fully implement PBL in the course: We had to use some of our free time to choose suitable, authentic problems. The limited duration of the course is also a hindrance: Here, it would be "easier" for the teacher to be the main source of learning in the form of direct transmission of knowledge.

Another issue in implementing PBL in the course, is that our students differ in skills and knowledge, and most of them need a strong guidance to learn. We tried to solve this issue by acting as a visiting member of the student groups, having a double roll:

- We acted like the ancient Greek philosopher Socrates, by asking questions that forced the students to ascertain a fundamental insight in the issue at hand.

- We gave some background knowledge according to the needs of the group visited, to keep the students on the right track.

- We had to make decisions on the spot, considering the different backgrounds of the students while making sure that our teaching project stays on course.

In his plenary speech at the ICME 7 conference in Quebec, Howson (1992) expressed something very interesting, in that he said "I have written elsewhere of the danger that parts of 'mathematics education' will detach themselves from mathematics teaching in much the same way that 'philosophy of mathematics' has drifted well away from 'mathematics' itself. (...). The importance of such studies is not to be denied, but where does that leave the mathematics educator who wants to serve and help teachers, not just to study, count, or assess them? Perhaps it would be a useful check for all of us contributing to this congress to ask of our contribution: How will/could it help teachers, under what conditions and within what timescale?"

We believe that research in education, especially when theoretical, should find its natural validation in practice, not only in the daily managing of classroom activity, but also in the teacher as a decision maker, influenced by important factors such as time constraints, knowledge, experience, beliefs and emotions.

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