Learning to Solve ‘Design Problems’ in Engineering Education

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Abstract
Problem solving is a special kind of skill to learn. It is unlike many other learning outcomes. There are many different kinds of problems which exist, with design problems being kind of problems with their own characteristics. Design problems are characterised by the fact that they are often complex, ill-defined and with no singular process model. Solving design problems requires system, procedural and strategic knowledge that students need to develop for contextual thinking and decision making. This paper formulates a learning approach which assists students to develop competencies to solve design problems particularly related to the engineering discipline. This work tries to help students to develop skills to an appropriate level, particularly in the discipline of solving engineering design type problems. The skills aimed to be develop map into established requirements from industry, professional bodies and government departments. A framework for teaching students skills for solving design problems is developed and presented. The framework is presented in terms of elements constructively aligned with the cognitive process required in problem solving. Through qualitative and quantitative research, in the context of a case study, a teaching experiment is presented based on the approach formulated in the framework.

Keywords: problem solving, engineering education, design problems, problem & project based learning

1. INTRODUCTION
The word problem is used in a variety of contexts and can be defined in a number of different ways. Understanding a puzzling phenomenon is a problem, how to find a better way to do something is a problem, the best way to design or build something is a problem and how to create an artistic work can be a problem. Palle Qvist [1] quotes Jenny Winter as defining a problem as follows, “A Problem is a wondering which takes the concrete form of a question” [2]. This is a very generic description, and many more precise descriptions are given in Qvist’s paper. Since the focus here is upon “Design” problems, the most apt definition given is probably the one attributed to Peter Nielsen [3], “A Problem is basically impression of a tension or a contrast between two conditions: Condition of Desires ----- Actual Condition”. The design problem of the item in question allows a transformation between the two conditions. The successful design of this item converts a condition of need or “Desire” into one of “Actuality”. These definitions are supported by David Jonassen [4] when he writes “First, a problem is an unknown entity in some context ..”, and “Second, finding or solving for the unknown must have some social, cultural or intellectual value”. He then adds one vital ingredient, “.. someone believes that it is worth finding the unknown”.

1.1 Types of Problems
As the problems differ in terms of attributes, they require different kind of problem solving processes and strategies. It is often the details of the problem solving processes, which makes the defining characteristics of a type of problem. Jonassen [4], referring to one of his earlier works, has given a topology of the types of problems. The types he has identified includes: puzzles, algorithm, story problems, rule-solving problems, decision making, troubleshooting, diagnosis-solution problems, strategic performance, systems analysis, design problems, and dilemma. The problem can significantly vary depending on the context and it is practically impossible to design and develop models for problem solving for every context and domain. The types of problems can perhaps be classified based on the similarities in the cognitive process required to develop skills for problem solving. Jonassen in his book has focused on the following three types of problems [4].

- Story problems
- Troubleshooting problems and
- Case and System and Policy Analysis problems.

Jonassen states that “story problems are the most commonly used and extensively researched kind of problems”. These are the type of problem frequently found at the back of textbooks. Students identify key words from the
problem description (the story) and select or adapt an appropriate solution methodology. Students require calculation accuracy, an ability to recognise patterns or structures in the problem. Story problems can form classes, or sub-classes, of problems which are domain specific.

Troubleshooting problems are, probably, the most commonly found problems in the engineering domain. The idea is to isolate and identify faults in some non functional system and repair or replace components to return the equipment to its operational condition. Effective and efficient troubleshooting requires three kinds of knowledge: system knowledge (i.e. knowledge of how the system works), procedural knowledge (i.e. problem solving procedures and test activities) and strategic knowledge (i.e. knowing when, where and how to apply the procedures). These skills are integrated and honed by the trouble-shooter’s own experiences.

Case problems are usually found everywhere except the classroom, probably because they are ill-structured and complex and, therefore, difficult to assess. They are very often used in domains where knowledge is less hierarchical and linear or sequential in nature (after some level foundation knowledge and a set of basic principles have been acquired by the learner). This is unlike Medicine, where the knowledge is more encyclopaedic [5]. Very often case problems have no opportunity to actually be implemented, and tend to focus on the thought processes rather than the creation of an actual product.

1.2 What is a Design Problem?
The focus in this paper is “Design” problems. None of the descriptions noted above match exactly what is classify as a design problem. These descriptions can, however, form the basis for a definition of design problems and comparison between design and other types of problems. Design problems are more than just story problems, they are not restricted to troubleshooting, because they incorporate new designs, and they are practical and achievable in a way that many case studies are not. Design problems are/can be a mixture of all three of Jonassen’s types, but tending towards cases, which have an absolute possibility of an achievable result. Design problems and case problems are similar in that there is no single correct answer. Using Bloom’s taxonomy, from basic memory to synthesis and sometimes to evaluation when considering different alternative solutions, can be achieved. Jonassen states that complex and ill-structured problems require a different approach to simpler problems. If the start is from the premise of developing a case, and we ensure that the case has an actual, achievable product – then it can be described as a Design Problem. This can be then shown as a continuum of problem types, as shown in figure 1.

![FIGURE 1. Continuum of Problem Types](image)

1.3 How are the Design Problems Solved?
Students who are learning to solve design problems need to face ill structured problems in order to develop independent or contextual thinking skills. What instructional strategies and interactions need to be learned to solve design problems? Students should be introduced to working in a formal manner in the generation of projects. By making students follow a model such as that shown in Table 1, (modified from Moesby [6]) they are introduced and guided to a scientific approach to project creation and problem-solving.

<table>
<thead>
<tr>
<th>Step number</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initiate Problem</td>
</tr>
<tr>
<td>2</td>
<td>Problem Analysis</td>
</tr>
<tr>
<td>3</td>
<td>Problem Conceptualisation</td>
</tr>
<tr>
<td>4</td>
<td>Consideration of Alternatives</td>
</tr>
<tr>
<td>5</td>
<td>Problem Delimitation</td>
</tr>
<tr>
<td>6</td>
<td>Design/Solution/Project Specification</td>
</tr>
<tr>
<td>7</td>
<td>Task Formulation</td>
</tr>
<tr>
<td>8</td>
<td>Implementation</td>
</tr>
<tr>
<td>9</td>
<td>Discussion/Conclusion</td>
</tr>
<tr>
<td>10</td>
<td>Reporting</td>
</tr>
</tbody>
</table>

TABLE 1. The Formal Phases of Transforming a Problem into a Project

Besides showing the general model of phases in project work, the model also shows where students may experience major difficulties in the collaboration during the project. The reason that students work with problems rather than projects is that design is often the entry point if students are given a project rather than a problem. Jonassen [4], also claimed by [7] states that solving policy (case) problems is an eightfold process:
1. Define the problem
2. Assemble some evidence
3. Construct the alternatives
4. Select the criteria
5. Project the outcomes
6. Confront the trade-offs
7. Decide and then
8. Tell your story

Another variation of the stages in problem solving and design is given in [3]. He lists the phases as:
- naming (identifying the main issues),
- framing (setting the limits),
- moving (taking action) and
- reflecting (evaluating and reporting).

2. FRAMEWORK FOR LEARNING TO SOLVE DESIGN PROBLEMS

Problem solving is part of professional activities of almost all disciplines. The emphasis on knowledge building that we usually find in the traditional teaching is not sufficient if we want our graduates to be prepared as creative and productive professionals with the required problem solving skills. Perhaps one of the fundamental skills that all engineers need to have is that of a designer. Designing in its essence is a problem solving activity, where there is usually a large scale process associated with the real-life engineering design projects. If we want our students to be capable problem solvers and not just executioners of a typical design process then their learning must include the components, which help them develop the problem solving skills.

The previous section of this paper provide an analysis of how design problems can be defined and solved and what considerations need to be made in helping the students to learn solving design problems. In this section the formulation of a framework is presented, which can provide a basis for designing teaching that lead students to learn skills for solving design problems. The purpose of formulating this framework is to identify and conceptualise the elements that ensure alignment of the learning process with the cognitive requirements for the learning of solving design problems. The framework does not attempt to provide a recipe for teaching rather a broad level approach, which can be used in the different contexts of the learning of solving design problems.

2.1 Definition of an Engineering Design Problem

In section 1 of this paper some of the definitions of the word “Problem” were defined, followed by a description of how problems can be classified. The “Design Problem” is then described as a class or a type of problems in the following section. Given this analysis it seems necessary to have a statement, which gives us an articulate definition of “Engineering Design Problem” before the framework is discussed. Therefore, “Engineering Design Problem” for this purpose is defined as follows:

“The product that comes out of a real life engineering design is usually a whole consisting of a large number of parts interconnected and interacting with each other, which is meant to address some specific needs and desires of people, function within defined constraints and meet given specifications.”

The scale of industrial level engineering design is often large enough so that the design process has to be organised over several levels. All levels of the process require the designer to have a significant breadth of knowledge including system knowledge, procedural knowledge, and strategic knowledge. The problem solving process, meant to address some specific needs and desires of people, however has an existence of its own. The process has its own set of steps and runs side by side with the design process. The thinking skills needed during problem solving in design problems requires making use of transitional knowledge, independent knowledge and contextual knowledge. It is imperative that the students are made to realise and distinguish the problem solving that exists within the overall design process.

2.2 The Framework

The problem solving in a design problem requires adopting a step-by-step approach. Several models of problem solving can be found in the literature as discussed earlier in section 1. Based on the concept of “Constructive Alignment” [8], a framework that makes the learning process constructively aligned with the problem solving process can be formulated. For this purpose the stages in design-problem solving as given by Nelson [3] are chosen, which consists of:
- naming (identifying the main issues),
- framing (setting the limits),
- moving (taking action) and
- reflecting (evaluating and reporting).
The reason for selecting this scheme of problem solving is that the indicated stages directly relate to the cognitive process required in problem solving and the scheme is general enough so that it is applicable in most contexts of design problems. While aligning the framework to this scheme of problem solving and inspired by the work of Jonassen in [4] we identify the following elements for the framework:

1. Presenting the problem to the learners
2. Supporting learners in representing the problem
3. Supporting learners in finding solution
4. Reflection in learning of problem solving
5. Assessing student learning in problem solving

The first four elements of the framework map directly into the scheme of problem solving given by Nelson in [3]. The last element is required for the learning process in a formal setting of learning.

### 2.2.1 Presenting the Problem to the Learners

It is only natural to assume that different students will favour different methods of presenting the material necessary to fully describe the problem and prevailing circumstances, and what support or scaffolding information we should provide and what format this should take. This point leads into the consideration of how to present the problem to the students. Complex and ill-structured problems require a different approach to simpler problems. There is little or no published research on problem preparation and problem presentation for complex, ill-structured problems, but the general feeling is that greater potential for understanding is created for students when ill-structured problems are posed to them, which means greater reach of depth in the eventual outcomes [4]. It may be necessary to present the material in alternative formats (obviously all of which should bear exactly the same final message) to allow students to use multi sensor analysis and correlation of the information so that they can get a full rounded version of the requirements.

### 2.2.2 Supporting Learners in Representing the Problem

Problem solving requires discipline knowledge. Novices too often see only the surface problem. Mapping into their own cognitive domain forces the student to construct their own knowledge about the topic. One technique called Concept Mapping could be used to guide the students into team (or class) discovery and discussion about the basic fundamentals and interactions in a particular domain. This domain could be the discipline specific domain of the eventual product, or the process domain of generic or directed problem solving. Forming their own concept map of a topic and then discussing it with classmates and/or supervisors could lead to the development of a class culture of mappings and interactions. The students and supervisors would then be the ‘owners’ of these newly discovered interactions and this could lead to alternative kinds of representation: qualitative, quantitative, abstract, concrete, visual, and verbal.

### 2.2.3 Supporting Learners in Finding Solution

Conceptualisation or analysis of the problem is an achievement in itself within the problem solving process as a great deal of ambiguity has been dealt with during this phase. Students often have a tendency to jump directly working on solution without going through the analysis. However, if they have spent enough effort in the analysis they are already almost into finding a solution. One of the key factors that make design problems ambiguous is the ill-defined constraints at the time of the conception of the problem. If the problem solving team has been successful in clearly defining constraints and criteria for solving the problem, they are well prepared for the stage of finding a solution. As pointed out earlier, the solution of a real life industry scale design problem requires design to be conceptualised at the following three levels:

- Conceptual Design
- Embodiment Design
- Detail Design

All three design levels require considerable level of system knowledge, procedural knowledge, and strategic knowledge. The traditional approach, however, tends to place more emphasise on application of procedural knowledge [4]. The learning of solving design problems cannot be considered complete if students are not engaged in acquiring and using system and strategic knowledge during the solution finding stage. Students must construct a conceptual understanding of the system that is under consideration for design and the strategic knowledge of when or why to use different procedures.

### 2.2.4 Reflection in Learning of Problem Solving

Reflection in learning to solve problems in this section is discussed in the following roles.

- Reflection for learning
- Reflection in learning of problem solving
- Reflection on problem solving
A condition that is considered necessary for the learning to be meaningful is to engage students in reflection during learning [4]. Reflection is necessary for learning because it helps in accommodating new knowledge with what is already known. The re-organisation of thinking that is required for the deep learning does not happen without reflection.

Meta-cognitive learning is the learning, where students reflect by critically questioning their understanding. Biggs in [8] has discussed two approaches to meta-cognitive learning. “Going beyond the information given” (BIG) approach is the conventional teaching approach, in which direct instruction is followed by thought-oriented activities that challenges students to apply and refine their understanding. The other approach is called “without the information given” (WIG), where students are facilitated to find their own way out and the best example of it is problem-based learning [8–9].

2.2.5 Assessing Student Learning in Problem Solving
In formal education, where the learning and assessment is performed at individual level, assessment is seen as one of the most important components. In this scenario, most students are usually concerned with “what is on the exam”. Through this method students learn how to memorise solutions to problems, rather than learn how to solve problem. In a group environment such as problem-based or project-based learning, this is somewhat different. In this type of environment students learn how to solve problems, regardless on the type of problem. However, even though students learn the art of problem solving through this method, the implication of assessing group is amplified. There has been a significant research carried out in terms of group work and the implication of assessing it.

Literature suggests that student group assessment in problem solving is usually divided into a number of categories which could include individual contribution to learning group, presentations and report submissions. This might also depend on the academic level of the students. Stojcevski et al in [10] have looked at the assessment implications in the final semester of an engineering program, where a group major project is the full load. They argue that students recruited into the major project are graduates and are assumed to have a certain level of maturity; therefore, there are no specific formal diagnostic processes for early detection of students at risk. In addition to this, project supervisors are vigilant during their project sessions for students who are struggling and who are then provided with additional support.

3. CASE STUDY – THE TEACHING EXPERIMENT

3.1 Objectives of the Experiment
This section describes the implementation of the case study. This involved establishing a baseline, designing appropriate materials for teaching problem solving to first students.

3.2 Working within the Framework
The key starting point during the implementation phase of this teaching experiment was to introduce the students to the definition of ‘design problem’ as described and defined in this paper. This was done during the introduction of Problem/Project Based Learning (PBL) course and took place early in the implementation phase. The key in the implementation process was to establish a library of cases and troubleshooting examples. Supporting the students in the presentation of their problems was also covered in the introductory workshop. Reflection continued activity as the students meet with the supervisor, and/or clients, during the period of the two problems. Another key point or issue in the presentation of the problem was the initial problem statement. It is critical that this process clearly defines the learning outcomes which students will achieve on the completion of the problem.

3.3 Planning of the Teaching Experiment
The design project scope section of this case study, performed in the year 1 Engineering Practice course, was performed in the first semester of the undergraduate electrical and electronic engineering degree. The current approach of students working on design projects was be used as a benchmark to analyse, plan, and even evaluate the experiment, based on the thematic approach. PBL is a fundamental requirement for the effective implementation of the thematic approach and framework of this experiment.

As mentioned earlier, the advantage in this implementation is that the implementer of this experiment is also a supervisor at undergraduate engineering which is taught through PBL. Therefore PBL staff preparation and induction will not be required; however PBL induction for students through the teaching experiment will have to be developed and implemented.

Table 2 below shows the semester overview of the teaching experiment.
<table>
<thead>
<tr>
<th>Week No.</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 1</td>
<td>Student team formation</td>
</tr>
<tr>
<td>Week 2</td>
<td>Introduction to PBL</td>
</tr>
<tr>
<td>Week 3</td>
<td>Introduction to the design problem according to the thematic framework</td>
</tr>
<tr>
<td>Week 4</td>
<td>Team dynamics Workshop</td>
</tr>
<tr>
<td>Week 5</td>
<td>Plagiarism workshop</td>
</tr>
<tr>
<td>Week 6</td>
<td>PRE Questionnaire taken</td>
</tr>
<tr>
<td>Week 7 - 9</td>
<td>Training workshops on “Problem Solving”</td>
</tr>
<tr>
<td>Week 10</td>
<td>POST Questionnaire taken</td>
</tr>
</tbody>
</table>

TABLE 2. Semester overview of teaching experiment

3.4 Student Analysis
The majority of the students are, on average, about 17 to 18 years old. Most have come here straight from school. They will probably have a Tertiary Entrance Ranking score in the 60s or 70s out of possible 100. Many will be the first in their family who have attended university. Most of them are from families with a low socio-economic background. Many have a language other than English as their first language. For many students they have come through a well structured school experience where they have been expected to be passive receivers of information where they are assessed on their ability to repeat what they have “learned”. Many may have come from a cultural background which reinforces this role of the student. They are now, however, part of the “Family of Engineering Students”. The language of tuition is English, and some have had very little experience with the language. This mix of students must now work in teams in a PBL setting to construct their own understanding of knowledge through the guidance of the problems posed for them in their PBL classes. The task faced in this case study is to attempt to facilitate the students’ learning in the discipline of Problem Solving for Engineering Design Problems so that they may be more able to participate fully and control their own learning.

3.5 Pre and Post Training Questionnaire
A Pre and Post training questionnaire was designed specifically for the implementation of the teaching experiment. This questionnaire was initially used to establish the baseline for the design of the material for the training classes and then used subsequently to evaluate the efficacy of the said classes. The questions are shown in table 3, below.

<table>
<thead>
<tr>
<th>No.</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>How do you remember things?</td>
</tr>
<tr>
<td>2</td>
<td>What makes you learn, or helps you to learn?</td>
</tr>
<tr>
<td>3</td>
<td>How do you think you learn how to solve problems?</td>
</tr>
<tr>
<td>4</td>
<td>What different types of problems do you think exist? Try to identify 5 different types of problems.</td>
</tr>
<tr>
<td>5</td>
<td>Why do you think we pose problems for you in Problem Based learning?</td>
</tr>
<tr>
<td>6</td>
<td>Identify 5 features which you think typify “Engineering Design Problems”.</td>
</tr>
<tr>
<td>7</td>
<td>Identify 5 elements about problems which could impact upon how you solve them.</td>
</tr>
<tr>
<td>8</td>
<td>Identify 5 elements of yourself and/or your learning/background which could impact upon how you solve problems.</td>
</tr>
<tr>
<td>9</td>
<td>Identify 5 ways in which teamwork could impact upon how you solve problems.</td>
</tr>
<tr>
<td>10</td>
<td>Try to identify 5 things which we, as supervisors, could do to help you solve problems.</td>
</tr>
<tr>
<td>11</td>
<td>If you have 10 desired products which have been requested for a project, but you are running short of time what would you do?</td>
</tr>
</tbody>
</table>

TABLE 3. PRE and POST questionnaire used

Questions 1, 2, 3, and to some extent 8 and 9 as well, look at the individual and their perceptions of learning and reflections on their own approach to learning. Questions 4 to 8 look at their current level of understanding of the nature of different types of problems, engineering design problems in particular, and their own interactions with problems. Questions 5 and 9 look particularly at Problem Based Learning, and the students’ understanding of this learning style and their own. Question 10 poses a simple “what if” scenario for the students to analyse and suggest possible solutions.

4. ANALYSIS AND RESULTS
4.1 Analysis of the PRE Training Questionnaire
The questionnaire was designed to be given to all students in year 1 Electrical Engineering program. Out of possible sixty students, forty five completed the questionnaire. The questionnaire was given out to students...
during their PBL team-supervisor meetings, and was also placed on WebCT (online) for those who were absent on the day. Out of the ten questions, which have been listed above in section 6 of this report, it was found that students required particular attention on three identified areas. Therefore, the training program which included reading material along with round group discussion was divided into the following three areas:

1. Different Types of Problems
2. Engineering Design Problems and
3. Problem Solving

4.2 Analysis of the POST Training Questionnaire

The responses from the POST training questionnaire were positive. Apart from the three areas which were covered in training and reading material, the rest of the responses stayed fairly consistent with the PRE training questionnaire. The responses to the three focused areas, as listed above in section 7, were greatly emphasised by the students. It was very fortunate that during the training activities, all students in the team attended for the three weeks. In addition, the round table discussion, instead of a lecture-based training program was very affective. The students were focused and very motivated.

4.3 Results of PRE and POST Training Questionnaire

Results of all individual PRE and POST training responses can be seen in figure 2 below. The figure illustrates a qualitative analysis which compares the PRE and POST training responses. The responses which relate to learning how to solve design problems are presented, as well as the question related to PBL.

<table>
<thead>
<tr>
<th>Question</th>
<th>PRE</th>
<th>POST</th>
</tr>
</thead>
<tbody>
<tr>
<td>How do you think you learn to solve problems?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>What different types of problems do you think exist?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identify 5 features based on which we call a problem as an “Engineering Design Problems”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identify 5 elements about problems which could impact upon how you solve them</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Try to identify 5 things which teachers could do to help you learn how to solve problems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Why do you think we pose problems for you in Problem Based Learning?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 2. Qualitative Results from PRE and POST questionnaire
The student responses indicated that though many students have a tendency towards using deep learning approaches most use surface approach to learning. Student responses also seem to support the constructivist theory of learning as their responses indicate that they learn best if the learning is contextual, which could help them to relate what they are learning with their existing sense of reality. They also seem to support social setups for learning and being able to learn something within a variety of contexts. Responses also indicate that concrete and tangible knowledge is important for the engineering students. Students in general seems not been able to properly identify and characterise types of problems.

5. CONCLUSIONS

This paper presented and described the implementation of a thematic approach to the design and implementation of a teaching experiment in a design problem for students in the first year undergraduate Bachelor of Engineering in Electrical and Electronic Engineering program. The design of the problem solving for engineering design problems focused on equipping new students in the first year of the PBL based course with the basic skills needed to participate in the course effectively. The thematic approach was based on a framework which was developed for teaching students skills for solving design problems. The framework was presented in terms of elements constructively aligned with the cognitive process required in problem solving. Through qualitative and quantitative research, in the context of a case study, a teaching experiment was presented based on the approach formulated in the framework.

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