Challenges Students Face in Solving Open-Ended Problems

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1.0 Introduction

Engineers by definition are problem solvers. Whether they are involved in analytical, experimental, computational or design work, engineers solve problems. Yet, the kinds of problems they solve on the job tend to be much more complex than the typical exercises found in engineering texts. Most of these exercises involve application of mathematics and science in well-defined situations, to seek a single correct solution. While these exercises play an important role helping students to bridge the gap between theory and application, they do not provide the complexity and depth necessary to develop real world problem-solving skills.

Woods et al[1] define problem solving as *the process used to obtain a best answer to an unknown or a decision subject to some constraints. The problem situation is one that the problem solver has never encountered before; it is novel. An algorithm or procedure to be used to solve the problem is unclear*. In contrast, they define exercise solving as *the recalling of familiar solutions from previously solved exercises*.

The requirement that engineering graduates must have open-ended problem-solving skills was formalized in ABET EC 2000[2]. In particular, Outcome 3e calls for *an ability to identify, formulate, and solve engineering problems*, clearly implying that students should be able to deal with ill-defined situations. Moreover, Outcome 3b (*an ability to design experiments*) and Outcome 3c (*an ability to design a system, component, or process*) also require open-ended problem-solving skills.

On the other hand, many studies have shown that to-date, engineering graduates do not posess adequate problem-solving skills even though they solve typically more than 2,500 exercises by the time they complete their undergraduate work.

2.0 Aerospace Engineering Open-Ended Problems at SJSU

In response to the challenge set by the new accreditation requirements, several faculty members in the mechanical and aerospace engineering programs at SJSU re-designed key core courses in an effort to help students develop problem-solving skills. This re-design includes:

a. Explicit definition of skills and attributes that students need to develop to become capable problem-solvers[1,3]. These skills and attributes come from both the affective and the cognitive domains of educational objectives. This observation suggests that students need to develop first certain attitudes before they acquire the skills necessary to tackle open-ended problems.

b. Inclusion of open-ended problems in each of several key, junior-level, core courses[3]. Open-ended problems are presented in lectures, assigned as homework to be done in teams, and are a part of the final exam in each course.
c. Coaching students in the use of Wood's Problem-Solving Methodology [4,3] (PSM) while solving open-ended problems. This process includes six steps: engage, define, explore, plan, implement, and reflect.
d. Development of rubrics to evaluate student performance at each step of the PSM.

The following section discusses the application of this process in the aerodynamics course at SJSU. The focus of this study is to identify specific difficulties students face while solving open-ended problems as well as specific steps they can take to overcome these difficulties.

3.0 Teaching and Assessing Open-Ended Problem-Solving Skills in an Aerodynamics Course

AE162 is a junior-level aerodynamics course required for aerospace engineering majors. The course includes two 75-min lectures per week and several three-hour laboratories by arrangement, in which students perform wind tunnel and water tunnel experiments. Open-ended problem solving skills are emphasized in all aspects of the course: For example, in the lab, students design their own experiments[5,6]. This involves defining goals and objectives for each experiment, researching previously published data, selecting dependent and independent variables, choosing appropriate methods and equipment to measure these variables, etc. Students also work in teams to identify, research, and study a current multi-disciplinary problem that involves applications from several courses[7]. In addition, several open-ended problems are discussed in class and assigned as homework. For the purposes of this study, however, student skills were assessed in Spring 2008 in the following two problems:

OEP-1[3]: Consider a large transport airplane, like the Airbus 380, in flight. Which aerodynamic surface is works harder to generate lift: the wing or the tail? Why?

OEP-2: Two identical, low aerodynamic IQ birds are flying at the same speed one directly behind another. If the power required by the first bird to overcome its induced drag is P_i, what is approximately the power required by the second bird to overcome its own induced drag?

OEP-1 is presented in class. Over a period of several weeks, students are coached to generate an answer following Woods' PSM (see steps below). They are given one week to work on each of the first three steps individually and turn in their write up. Subsequently, they work in assigned teams to revise steps 2 and 3 as necessary and complete steps 4, 5, and 6. Each step is discussed in class. Expectations of what students need to do are explained using the rubrics in Tables 1 through 5. As students complete each step, they turn in their write up and share their ideas and solutions in class. This is a critical part in their learning process, because they are given feedback and are brought to the same level of understanding before proceeding to the next step.

OEP-2 was assigned on the final exam. It should be noted that the two problems are very similar. This takes away some of the challenge on the second problem because the context is not brand new. Hence, the expectation was that students would perform very well on OEP-2.

The Spring 2008 enrollment in the course was 28 students, of whom 25 received passing grades (C or higher). The following subsections present a summary of student performance in each step of the PSM on each of the two problems, the challenges they faced, and some ideas for improving the process next time.

Step 1: Engage in the Problem

Engagement is attention, which comes as a result of a perceived need or purpose in the first place. Cambourne[8] defines engagement as one of the eight conditions that must be satisfied for learning to occur. Students engage in a problem if they are convinced they can solve it and they see it as having some relevance to their own lives. Although a rubric for measuring student engagement in a problem has not been developed yet, an effort is made whenever possible to present engineering problems in ways that make them seem more relevant to their lives. Needless to say this is not always easy. Student engagement in these problems was average.

Step 2: Define the Problem

Here students try to understand the problem and re-state it in their own terms. They make a comprehensive list of what is given about the problem and what may be known from other sources. The latter presupposes some research, which includes reading various sections of the textbook and searching online or in the library. Students may also determine any applicable constraints. They are expected to draw a sketch of the problem showing any parameter they think is relevant to the question. The one important outcome of this step is the criterion to be used in answering the question. In other words, what "measure" will they use to determine which aerodynamic surface works harder (ex. effective angle-of-attack of each surface)? Table 1 shows the rubric used to grade their write up for Step 2.

Table 1 – Rubric for measuring student performance on Step 2 of the PSM (N = 25).

Score	Performance Criterion: Define one or more criteria (measures) for answering the question.	*OEP-1* Step completed individually	*OEP-1* Step completed in teams (revised)	*OEP-2* Step completed individually (final exam)
		# of students		
10	Identify a proper "measure". Include appropriate sketches illustrating all relevant parameters.	1 (4%)	6 (24%)	10 (40%)
7 - 9	Identify a "measure" that can indirectly lead to a more appropriate one. Sketches illustrate some of the relevant parameters.	4 (16%)	19 (76%)	6 (24%)
5 - 6	Identify what may at first appear as a reasonable "measure" but which may later be shown to be inappropriate. Sketches illustrate some of the relevant parameters.	8 (32%)	0	5 (20%)
1 - 4	Did not specify a useful "measure" for the comparison. No sketches included.	10 (40%)	0	2 (8%)
0	Did not attempt.	2 (8%)	0	2 (8%)

Table 1 shows that almost half of the students (12 / 25) were not able to properly define OEP-1, when they worked on it individually. However, all 25 performed very well when given the opportunity to work in teams and revise their definition. Students also performed this step very well on the final exam problem. Only two students were not able to properly define OEP-2 and two more did not attempt to define it.

Several students identified this step as the most difficult in the entire PSM. More specifically, the most challenging part was the uncertainty about what might be an appropriate measure to compare the work of the wing and the tail. In addition, students found the instructions not clear enough. In their own words: *"we were told to include sketches but what kinds of sketches?"*

Step 3: Explore the Problem

Students explore relevant questions, which they might have to answer before they are able to compare their chosen "measures" for the wing and the tail (ex. what does the effective angle-of-attack of each surface depend on?). Next, they brainstorm possible ways to model the flow around the wing and the tail of the airplane, making reasonable assumptions in the process. Before proceeding to the next step, they try to guess which surface works harder using their intuition alone. Table 2 shows the rubric used to grade their write up for Step 3.

Table 2 – Rubric for measuring student performance on Step 3 of the PSM (N = 25).

Score	Performance Criterion: Generate appropriate questions related to the "measures" defined in Step 2, identify possible approaches (models) for solving the problem, and make reasonable assumptions.	*OEP-1* Step completed individually	*OEP-1* Step completed in teams (revised)	*OEP-2* Step completed individually (final exam)
		# of students		
10	Generate at least two relevant questions, identify at least two different approaches, and make all necessary assumptions for each approach.	0	4 (16%)	4 (16%)
7 - 9	Generate at least one relevant question, identify at least two different approaches, and make most of the necessary assumptions for each approach.	3 (12%)	18 (72%)	1 (4%)
5 - 6	Generate at least one relevant question, identify at least one approach, and make most of the necessary assumptions for this approach.	3 (12%)	3 (12%)	10 (40%)
1 - 4	Generate one or two relevant questions, did not identify an approach, did not make some or all of the necessary assumptions.	7 (28%)	0	8 (32%)
0	Did not attempt.	12 (48%)	0	2 (8%)

Table 2 shows that 76% of the students did not perform adequately in Step 3. In fact, 48% did not even attempt Step 3 on OEP-1. One possible reason for this is of course the fact that Step 3 is more challenging than Step 2. Fortunately, students were able to get back on course once they received coaching in class and allowed to work in teams (column 2). In fact, 16% excelled and 72% did very well on their revised write up. However, 40% of the students performed poorly on this step on the final exam problem.

The most difficult challenge identified by students on this step was making assumptions about the flow. In their own words: *"We didn't know if our assumptions would lead to the right answer. We were trying to avoid making the problem too big (on one hand) versus* *oversimplifying it (on the other*). Nevertheless students acknowledged that this ambiguity led to a better understanding of the material.

Step 4: Plan the Solution

Students select an appropriate model (theoretical or empirical) for developing a solution. In most cases, the proper model to choose is the simplest available. Next, they break down the problem into smaller sub-problems, each involving the calculation of various parameters, which serve as stepping-stones towards the final answer. For the particular problem discussed, students choose a way to model the flow around the wing, its wake, and the horizontal tail. Sub-problems may involve the calculation of the circulation of each surface, the downwash on each surface, the induced angle-of-attack of each surface, and finally the vortex drag of each surface. It is important that in this step, students develop an algorithm (flow chart) for the solution of the problem and not substitute any numerical values. This may involve, for example, identifying appropriate equations or graphs for calculating various parameters in each sub-problem. Table 3 shows the rubric used to grade their write up for Step 4.

Table 3 – Rubric for measuring student performance on Step 4 of the PSM (N = 25).

Score	Performance Criterion: Select an appropriate model (theoretical or empirical) for developing a solution, break down the problem into sub-problems (stepping-stones), and determine what needs to be found in each sub-problem.	*OEP-1* Step completed in teams	*OEP-2* Step completed individually (final exam)
10	Select the most appropriate model for developing a solution, break down the problem into appropriate sub-problems; complete list of what needs to be found in each sub-problem.	10 (40%)	0
7 - 9	Select an appropriate model for developing a solution, break down the problem into appropriate sub-problems; incomplete list of what needs to be found in each sub-problem.	0	3 (12%)
5 - 6	Selected model for developing a solution is not described adequately; break down of problem into sub-problems is not appropriate or helpful; list of what needs to be found is incomplete.	7 (28%)	10 (40%)
1 - 4	Did not identify a model for developing a solution or did not break down the problem into sub-problems and / or did not list what needs to be found.	4 (16%)	8 (32%)
0	Did not attempt.	4 (16%)	4 (16%)

Table 3 shows that overall, students performed better on Step 4. Still, the percentage of students who did not perform adequately on OEP-1 (32%) and OEP-2 (48%) is fairly high.

Some students identified as a challenge in this step the application of appropriate theory to the specific problems. This may be understandable considering the fact that they had limited exposure to the relevant theory and its applications before they were given OEP-1. On the other hand, once they had seen the proper application of theory for OEP-1 in class, they should have been able to apply the same theory to a very similar problem in OEP-2.

Step 5: Implement the Plan

Students substitute the values of known and assumed quantities into their model (equations) and develop the solution, checking for accuracy and consistency of units along the way. The outcome of this step includes numerical answers for various calculated parameters and may also include additional sketches, figures, or drawings, depending on the problem. Table 4 shows the rubric used to grade their write up for Step 5.

Table 4 – Rubric for measuring student performance on Step 5 of the PSM (N = 25).

Score	Performance Criterion: Substitute appropriate values of known and assumed quantities in the equations and carry out calculations correctly. Produce sketches, figures, and drawings as necessary.	*OEP-1* Step completed in teams	*OEP-2* Step completed individually (final exam)
10	All calculations are correct. Appropriate sketches, figures, and drawings included in the solution.	4 (16%)	3 (12%)
7 - 9	Most calculations are correct. Appropriate sketches, figures, and drawings included in the solution.	13 (52%)	1 (4%)
5 - 6	Some calculations are correct. Some sketches, figures, and drawings included in the solution.	4 (16%)	3 (12%)
1 - 4	Several of the calculations are incorrect. Important sketches, figures, and drawings are missing from the solution.	4 (16%)	9 (36%)
0	Did not attempt.	0	9 (36%)

Table 4 shows that overall, students performed well on Step 5 in OEP-1. Once more, however, a large percentage of students (72%) performed inadequately on the same step in OEP-2, indicating that many students were not ready to stand on their own when solving open-ended problems. Students did not identify any particular challenges in relation to Step 5, however, it follows that their performance here very much depends on their setup from Step 4.

Step 6: Evaluate and Reflect

Often, making an unrealistic assumption in Step 3 or choosing an inappropriate model in Step 4 will result in numbers that do not make sense. Students are expected to identify the cause of the problem and correct it. They compare their final answer to their guestimate from Step 3. If their guestimate was incorrect they must provide an explanation as a way of developing intuition. In addition to discussing the solution of the problem itself in this final step they also reflect on their problem solving process and in particular on what worked well for them and what did not.

As Woods[4] points out, the evaluation/reflection step is usually not done very well, if done at all. Yet, this step is critical for self-assessment and self-improvement. Table 5 shows the rubric used to grade student write up for Step 6.

Table 5 – Rubric for measuring student performance on Step 6 of the PSM (N = 25).

Score	Performance Criterion: Discuss whether answer makes sense, evaluate appropriateness of models used and any assumptions made. Reflect on personal problem solving process.	*OEP-1* Step completed in teams	*OEP-2* Step completed individually (final exam)
10	Comments on whether the answer is reasonable or not and why. Evaluates the appropriateness of any models used and any assumptions made, based on the answer received. Reflects in depth on his/her personal problem solving process; identifies several strengths and several areas for improvement.	0	4 (16%)
7 - 9	Comments on whether the answer is reasonable or not but does not explain why. Evaluates the appropriateness of any models used and some of the assumptions made, based on the answer received. Reflects on the personal problem solving process; identifies at least one strength and one area for improvement.	8 (32%)	0
5 - 6	Comments on whether the answer is reasonable or not but does not explain why. Does not evaluate the appropriateness of any models used and/or some of the assumptions made, based on the answer received. Inadequate reflection on the personal problem solving process. One strength and/or one area for improvement identified.	7 (28%)	0
1 - 4	No comment on whether the answer is reasonable or not. No evaluation of the appropriateness of any models used and/or any assumptions made, based on the answer received. No reflection on the personal problem solving process; No strengths or areas for improvement identified.	3 (12%)	2 (8%)
0	Did not attempt.	7 (28%)	18 (72%)

The statistics in Table 5 confirm Wood's comments, namely that students have difficulty with this final step. Interestingly enough 16% of the students scored a perfect 10 on OEP-2 when no teams scored at this level on OEP-1. Nevertheless, 80% of the students received non-passing scores (0 – 4) on Step 6 in OEP-2.

Some of the difficulties identified above are cognitive, such as the inability to use first principles and relying instead on memorized solutions of previously seen exercises. It is not difficult to see how students have come to rely so much on previously seen solutions: it is the primary mode of operation in most engineering classes. Most of the homework and exam problems assigned are similar to example problems presented in lectures or in textbooks. While it may be desirable and even necessary to solve some problems that are similar to the ones they have seen, it is also essential that students are given a sufficient number of open-ended problems, each with brand new context, so they have opportunities to apply first principles in their approaches.

On the other hand, some of the difficulties students experienced in solving open-ended problems in aerodynamics are affective, such as unwillingness to spend sufficient time reading and gathering information about a problem, reluctance to write down ideas and create sketches while solving a problem, and being uncomfortable with ambiguity. An emphasis on the entire problem solving process when grading problems was shown to be somewhat effective in improving student performance in these areas. Moreover, it appears that when students improve their affective skills their performance in the cognitive areas of problem solving improves as well.

4.0 Conclusion

The analysis of the limited data collected in an aerodynamics course at SJSU leads to two observations:

a. Students have great difficulty approaching OEPs. These difficulties are both cognitive and affective.
b. It is easier to work first on student affective skills before tackling cognitive skills.
c. Most students enjoy the challenge of OEPs and perform reasonably well with proper coaching.
d. Like any other skill, students need to witness first an OEP solved by an expert, before attempting to solve one on their own.
e. When students solve an OEP outside of class, it is important to calibrate their approach / solution after they complete each step of the PSM.

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