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Challenges Students Face in Solving Open-Ended Problems*

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Several core aerospace engineering courses at SJSU have been re-designed in an effort to help students develop problem-solving skills. This re-design includes (a) explicit definition of skills and attributes students need to develop to become capable problem-solvers, (b) inclusion of open-ended problems in each of several key, junior-level, core courses, (c) coaching students in the use of Wood's Problem-Solving Methodology, and (d) development of rubrics to evaluate student performance at each step of this methodology. The paper discusses the application of this process and, in particular, it presents an assessment of student performance in two courses: fluid mechanics and aerodynamics. The focus of this study is to identify specific difficulties students face while solving open-ended problems and specific steps they can take to overcome these difficulties.

Keywords: engineering problem solving; open-ended problems; assessment of problem solving skills; ABET criteria

1. INTRODUCTION

ENGINEERS ARE by definition 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 in 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.

The fact that engineering graduates do not possess adequate problem-solving skills has been confirmed by several studies [1, 2, 3] and is a problem that persists around the world to this date [3]. In one of these studies students showed no improvement in problem solving skills even though they observed at least 1,000 examples worked on the board and solved more than 3,000 exercises in homework by the time they completed their undergraduate work [2].

Woods et al [2] 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 [4]. 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.

Open-ended problems (OEPs) are an integral part of the problem-based learning (PBL) approach, developed in its modern form at the McMaster University Medical School in the 1970s. Due to its success in medicine, PBL has been adapted in other fields of higher education as well [5]. In particular, it has been proposed as an approach with excellent potential for developing the critical problem-solving skills and many of the 'soft' skills (ex. communication and team skills) required by ABET EC 2000 [6]. Although the traditional lecture mode is still prevalent in engineering education, many engineering courses around the world currently use PBL with success [7–10]. In fact, some schools have structured their engineering programs entirely on the PBL approach [10].

A related methodology, recently adapted from mathematics education, is model-eliciting activities (MEA). Model-eliciting activities also involve OEPs set in a realistic context. They were recently introduced in engineering education [11–14] as a way to help students become better problem solvers as well as a vehicle for increasing interest

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and engagement in underrepresented student populations [11].

2. COURSE DESIGN FOR TEACHING OPEN-ENDED PROBLEM-SOLVING SKILLS

In response to ABET EC 2000, key core aerospace and mechanical engineering courses at SJSU have been re-designed to help students develop problem-solving skills [15–18]. This re-design includes:

a. Explicit definition of skills and attributes that students need to develop to become capable problem-solvers [15]. These skills and attributes come from both the affective and the cognitive domains of educational objectives.
b. Inclusion of OEPs in each of several key, junior-level, core courses [15]. Open-ended problems are presented in lectures, assigned as team homework, and may be included on final exams as well.
c. Coaching students in the use of Wood's Problem-Solving Methodology (PSM) [19] while solving OEPs. This process includes seven steps: engage, define, explore, plan, implement, check, and reflect.
d. Development of rubrics to evaluate student performance at each step of the PSM.

The focus of this study was to identify specific difficulties students face while solving OEPs and specific steps they can take to overcome these difficulties. Below is a short description of the OEPs used in two required BSAE courses.

(1) *Open-Ended Problem-Solving in Fluid Mechanics (ME111)*

ME111 is a three semester-unit, junior-level, required course for aerospace, mechanical, and civil engineers. It meets twice a week for 75-min. In every class meeting, students solve problems in small groups. Moreover, they work in teams to define, analyze, and solve a fluid mechanics problem, which they present in class at the end of the semester. Students may choose to design, build, and demonstrate a device as part of this project. The following are the OEPs used in this course during this study (Fall 2008 / Spring 2009):

Example OEP: Design the downspouts for a house to be able to take all the water during heavy rain without overflowing [20]. The solution of this problem was presented in class.

OEP-1: A soccer ball develops a small leak from a hole with an area of 0.006 mm^2*. Would the ball feel noticeably softer at the end of the first half of the game?*

OEP-2: The party is over and it is raining hard. Your car is parked a couple of blocks away and you have no umbrella. The way to your car is open, exposed to the rain. You are wearing your new designer clothes and you want to make sure you soak them as little as possible. Are you going to run or walk to your car?

OEP-3: Define your own OEP. For example, one team chose to *design the hydraulics for a team member's house, complete with a sprinkler system, calculation of all the head losses, and selection of a pump for drawing water from a well in the property.*

(2) *Open-Ended Problem-Solving in Aerodynamics (AE162)*

AE162 is a three semester-unit, junior-level required course for aerospace engineers and an elective for mechanical engineers. This class also meets twice a week for 75-min and follows the same regiment of problem-solving exercises in small groups in every class meeting. In addition, AE162 includes four two-hour laboratories, 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 [16–17]. 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 each variable, etc. Students also work in teams to identify, research, formulate, and solve a current multidisciplinary problem that involves applications from at least two courses, AE162 and AE165 (flight mechanics), which they typically take concurrently. Students have the option to integrate applications from other courses they are taking or have completed in previous semesters [18]. ME111 is a prerequisite course for AE162, so in principle AE162 students have more experience with OEPs. The following are the OEPs used in this course during this study (Spring 2008 / Spring 2009):

OEP-1: Consider a large transport airplane in flight. Which aerodynamic surface works harder to generate lift, the wing or the tail? Explain [15]! An approach similar to the one described earlier for ME111 was used to coach students in the solution of this problem.

OEP-2: Two identical 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?* This was a final exam problem, which requires similar modeling as OEP-1. This similarity, while appropriate for a final exam problem, takes away some of the challenge because the context of the problem is not entirely new. Hence, the expectation was that students would perform very well on OEP-2.

OEP-3: Define your own OEP. For example, one team chose the design and performance analysis of a wing-in-ground-effect. The students used aerodynamics (AE162), computational fluid dynamics (AE169), aerospace structural analysis (AE114), and flight mechanics (AE165) to propose a solution, thus integrating theory from four courses into their problem.

3. RESEARCH METHODOLOGY

Three sections of ME111 are offered every semester, while only one section of AE162 is offered per year. The author collected and analyzed all the data presented in this paper in course sections he taught. In particular, his ME111 section had an enrollment of 62 students in Fall 2008, of whom 38 (61%) received passing grades (C– or higher) and 64 students in Spring 2009, of whom 53 (82%) received passing grades. AE162 had an enrollment of 28 students in Spring 2008 of whom 25 (89%) received passing grades and 24 students in Spring 2009, of whom 22 (92%) received passing grades.

Student performance in each step of the PSM was evaluated using the rubrics in Tables 4–8 (Appendix). These rubrics were presented and explained in each course.

The rubric for measuring student engagement (Step 1 of the PSM) was used for the first time in Spring 2009 (Table 3). The survey was distributed in both courses at the end of the semester, after completion of the last OEP and included questions related to student confidence in their cognitive skills (Table 1) as well as student attitudes and habits during problem solving (Table 2).

Students are asked to include two separate reflections (Step 7 of the PSM) in their report for each problem (Table 8). The first involves the technical aspects of the problem itself and is performed by the team. The second involves each member's personal problem-solving process and is carried out individually. As part of this personal reflection, students were reminded to answer the following questions in their report for the last OEP in each class. A qualitative analysis of student responses was conducted.

(a) What was the greatest challenge you faced in solving OEPs in this class?
(b) What other difficulties did you experience in solving OEPs?
(c) What general skills did you learn (applicable to other classes / situations) from solving OEPs in this class?
(d) Do you have any specific suggestions for the instructor on how he can help students improve their problem-solving skills?
(e) Do you have any specific suggestions for students who try to solve OEPs?

Although OEP-1 and OEP-2 were assigned both semesters in ME111, slightly different approaches were followed in Fall 2008 and Spring 2009. In Fall 2008 students were asked to work on each of the first four steps of OEP-2 individually and turn in their write up. It was hoped that requiring individual effort in the first four steps would encourage students to come up to speed before joining efforts with their teammates. Subsequently, students worked in their teams to revise steps 1 through 4 as necessary and finish the problem by completing steps 5, 6, and 7. In Spring 2009 students were not required to perform steps 1 through 4 individually.

Each step was discussed in class. Expectations of what students had to do in each step are explained in the rubrics (Appendix). As students completed each step, they turned in their write up and shared their ideas and solutions in class. This was a critical part in their learning process because they were given feedback and were brought to the same level of understanding before proceeding to the next step. Students had three weeks to tackle each OEP. They had opportunities to ask questions in class and were coached on how to apply the PSM.

4. TEACHING AND ASSESSING THE PROBLEM— SOLVING METHODOLOGY

4.1 Step 1: Engage

Engaging in each problem is the first step of the PSM. Engagement is attention, which comes as a result of a perceived need or purpose in the first place. Cambourne [21] 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 [21, 22]. Table 3 summarizes student responses related to their engagement in the OEPs in each course.

Table 3 shows a fairly good level of student engagement with both the ME111 and the AE162 problems (students averaged 6–7 hours on each OEP). In AE162 they averaged 38 hours on their open-ended project, which represents a significant investment of time. There are three possible explanations for this: (a) the project requires integration of two subjects, aerodynamics (AE162) and flight mechanics (AE165), hence it affected student grades in more than one course; (b) the project carries a greater weight towards the course grade (20% vs. 5% for each of the rest OEPs); (c) a much higher level of engagement is achieved when students work on a problem of their choice.

It is also worth noting that 54% of the ME111 students and 32% of the AE162 students found the course material difficult. The main reason for this perception, especially in ME111, is inadequate preparation in the course prerequisites (primarily calculus and physics). This is confirmed by the poor test scores of ME111 students on the Force Concept Inventory [23] and AE162 students on the Fluid Mechanics Concept Inventory [24]. Students typically average 45–50% on these tests at the beginning of ME111 and AE162 respectively.

4.2 Step 2: Define

In Step 2 students try to understand the problem and re-state it in their own terms. They make a comprehensive list of what is given but also what may be known from other sources, and determine any applicable constraints. This step requires some research to gain some background about the problem, which may include reading various sections of the textbook, a visit to the library, or searching online (students' favorite method). Students are expected to draw a sketch of how they visualize the problem including any parameters they think are relevant. The most important outcome of this step is the criterion to be used in answering the question. For example, in the soccer problem (ME111) students decide what 'measure' to use to determine if the ball feels noticeably softer (ex. percent of air mass escaped, percent of pressure lost, etc.). Figure 1 presents student performance in Step 2 using the rubric in Table 4.

ME111 (Fall 2008) students performed significantly better as a class on the second problem, despite its greater difficulty (Fig. 1a). Specifically, 97% received passing scores, with 81% receiving scores 7 or higher in OEP-2 compared with 84% and 50% respectively in OEP-1. The results were similar in Spring 2009: 83% received passing grades in Step 2 with 70% receiving scores 7 or higher in OEP-2 compared with 50% in OEP-1. This indicates that students were able to improve their skills in 'problem definition' as they gained experience with each OEP.

In contrast, Fig. 1b shows that AE162 (Spring 2008) students performed better in Step 2 in OEP-1 (89% scored 7 or higher vs. 61% for OEP-2). However, OEP-1 was team homework while OEP-2 was a final exam problem. In Spring 2009, 67% received passing scores in OEP-1 and 100% in OEP-2. In fact, all students scored 7 or higher in Step 2. Students also performed very well in the much more challenging OEP-3, although 25% did not receive a passing grade in Step 2.

Thirty three (33%) percent of the students in ME111 and 41% of the students in AE162 identified Step 2 as the greatest challenge in solving OEPs, expressing discomfort with the fact that so little information was given about each problem, unlike typical homework problems and exam questions.

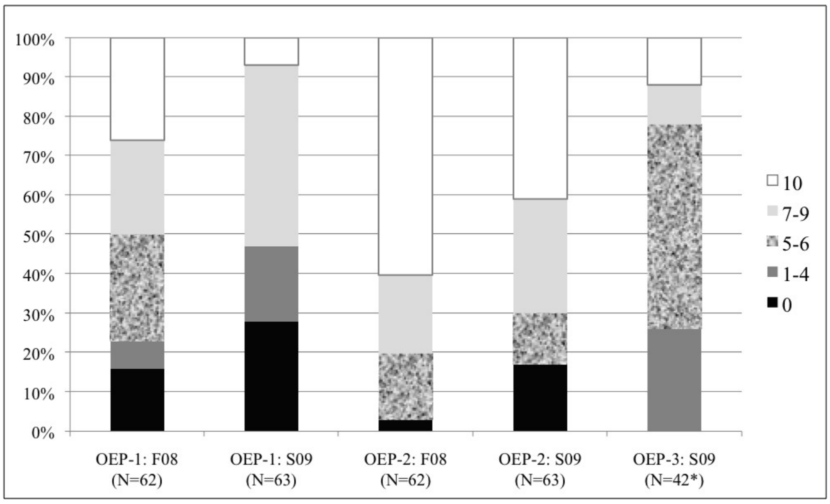

Fig. 1a. Student performance on Step 2 of the PSM in ME111
[*42 of the 63 students chose to work on an OEP of their own design].

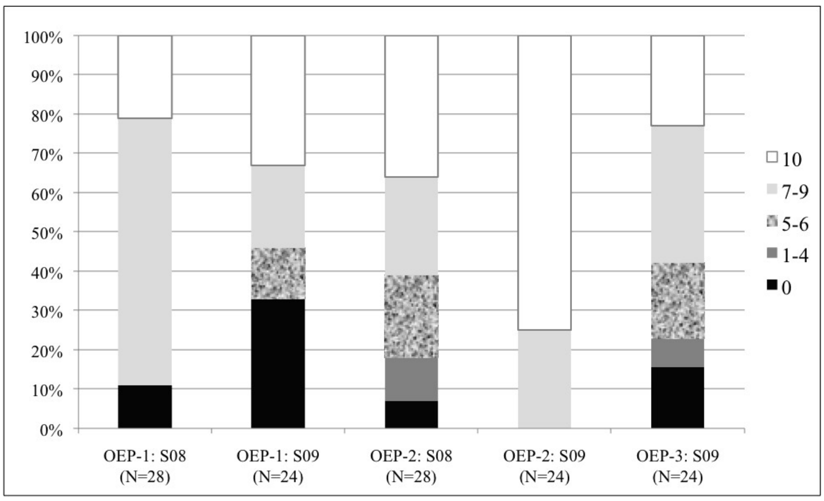

Fig. 1b. Student performance on Step 2 of the PSM in AE162.

4.3 Step 3: Explore

In this step students explore relevant questions and brainstorm possible ways to model the physical situation described in the problem by making appropriate assumptions. To develop intuition, students also attempt to predict the answer to the problem. Figure 2 presents student performance in Step 3 using the rubric in Table 5.

Figure 2a shows that, overall, students 'explored' OEP-2 better than OEP-1 (in Fall 2008 only 3% did not perform adequately in OEP-2 compared with 29% in OEP-1; the corresponding numbers for Spring 2009 are 21% and 44% respectively). Again, students seem to perform better in their second opportunity to solve an OEP despite the increased level of difficulty. Figure 2b shows that student performance benefited from the team-effort in OEP-1 (Spring 2008) while 43% of the students did not perform adequately in this step in OEP-2 (individual effort, final exam). This trend, however, was reversed in Spring 2009 when 41% of the students did not receive a passing score in OEP-1 while all students performed adequately on OEP-2. As was the case with Step 2 students performed very well in the much more challenging OEP-3 although 24% did not receive a passing grade in Step 3.

Thirty (30%) percent of the students in ME111 and 9% of the students in AE162 identified Step 3 as the greatest challenge in solving OEPs. An additional 24% of students in ME111 and 18% in AE162 identified Step 3 as the second greatest challenge in tackling OEPs. By far the greatest difficulty expressed by students was making appropriate assumptions to simplify the problem. 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.

4.4 Step 4: Plan

Students select an appropriate model (usually

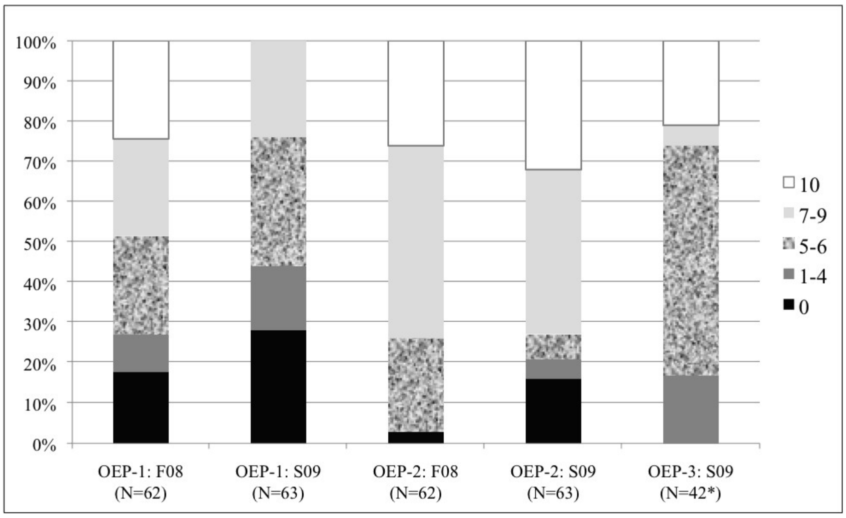

Fig. 2a. Student performance on Step 3 of the PSM in ME111
[*42 of the 63 students chose to work on an OEP of their own design].

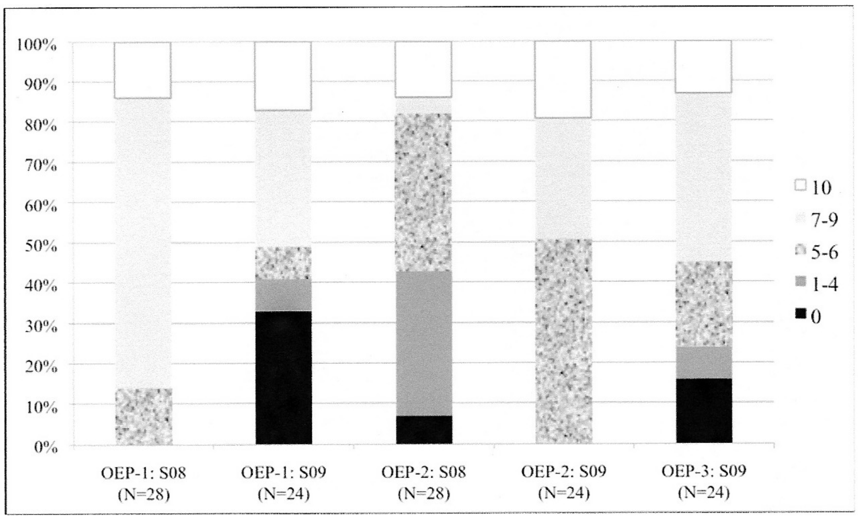

Fig. 2b. Student performance on Step 3 of the PSM in AE162.

the simplest available) for developing a solution. 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. It is important that students develop an algorithm (flow chart) for the solution of the problem and not substitute any numerical values. This algorithm may involve, for example, identifying appropriate equations or graphs for calculating various parameters in each sub-problem. Figure 3 presents student performance in Step 4 using the rubric in Table 6.

Figure 3a shows that in Step 4, as in previous steps, students performed better in their second opportunity to solve an OEP. Figure 3b (Spring 2008) shows again that performance may improve when students work in teams. This trend is again reversed in Spring 2009 when students performed significantly better on OEP-2 on the final exam. However, a larger percentage of students (50%) performed poorly in Step 4 of OEP-3.

Seventeen (17%) percent of the students in ME111 and 14% of the students in AE162 identified Step 4 as the greatest challenge in solving OEPs. An additional 19% (ME111) and 5% (AE162) identified this step as the second greatest challenge in tackling OEP. Students find it difficult *'figuring out which equations/principles to use'*.

4.5 Step 5: Implement

This is the most straightforward step of the PSM. Students simply 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. Figure 4 presents student performance in Step 5 using the rubric in Table 7.

Figure 4 shows similar trends with Fig. 3. This is to be expected, as student performance in Step 5 very much depends on their problem setup from Step 4. The large percentage of students (74%) who performed inadequately in Step 5 of OEP-2 (AE162, Spring 08) indicates again that many

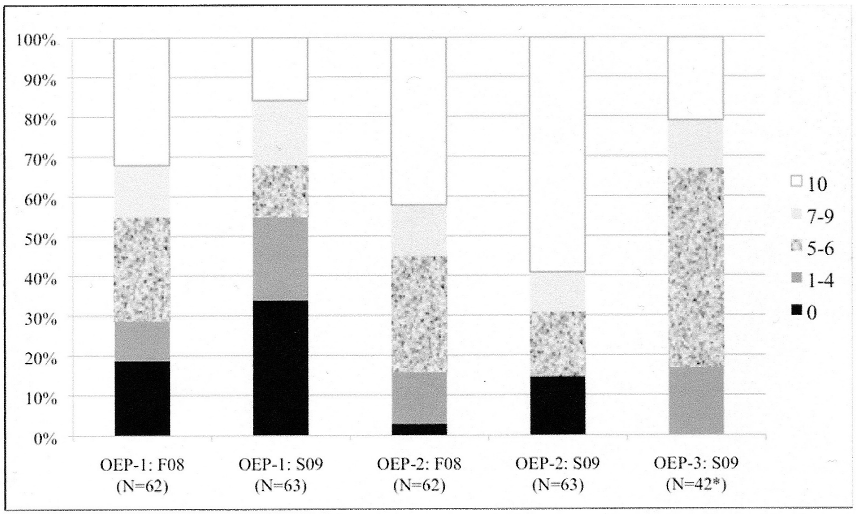

Fig. 3a. Student performance on Step 4 of the PSM in ME111.

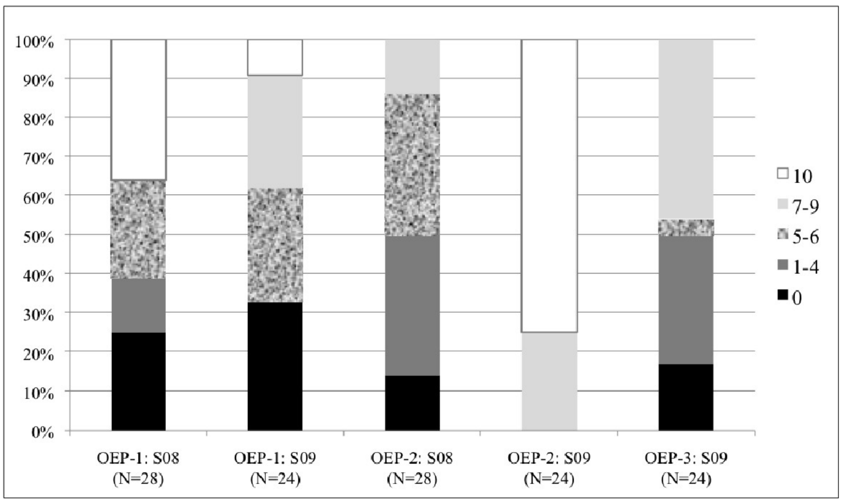

Fig. 3b. Student performance on Step 4 of the PSM in AE162.

students were not ready to tackle an OEP on their own. Students did not identify any particular challenges in relation to Step 5.

4.6 Step 6: Check

Students check their calculations for errors and make sure the units in all parameters are correct. No rubric is used to evaluate student performance in Step 6. Unchecked calculation errors simply result in lower scores in Step 5.

4.7 Step 7: Reflect

Making an unrealistic assumption in Step 3 or choosing an inappropriate model in Step 4 often results in numbers that do not make sense. This is a common occurrence in OEPs even among experienced problem-solvers. Students are expected to identify the cause of the problem and correct it or suggest a more sophisticated approach to solve the problem. Furthermore, they compare their answer to their guestimate from Step 3. If their guestimate was incorrect they provide an explanation as a way of developing intuition. In addition to discussing the solution of the problem itself, students reflect on their own strengths and weaknesses in the problem-solving process. Figure 5 presents student performance in Step 7 using the rubric in Table 8.

As Woods [19] points out, the reflection step is usually not done very well, if done at all. Yet, this step is critical for self-assessment and self-improvement. The large number of students who receive non-passing scores (0–4) on Step 7 confirms Wood's comments, namely that students have great difficulty with this final step. Nevertheless, very few students mentioned reflection as one of their major challenges.

5. ADDITIONAL CHALLENGES

Following the PSM in its entirety was identified by 28% of the students as the greatest challenge in solving OEPs. An additional 17% listed the PSM as the second greatest challenge. One of the difficulties mentioned was lack of confidence on whether they approach the problem correctly, especially not knowing beforehand what the 'correct answer' is. Integrating knowledge from

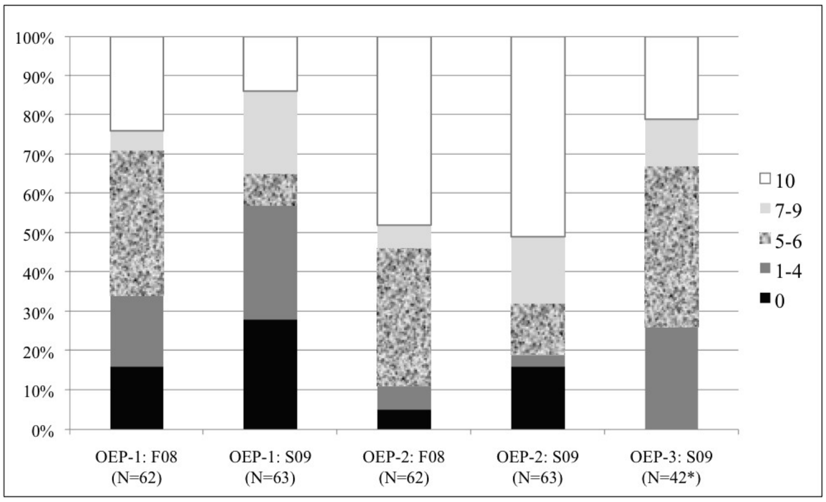

Fig. 4a. Student performance on Step 5 of the PSM in ME111.

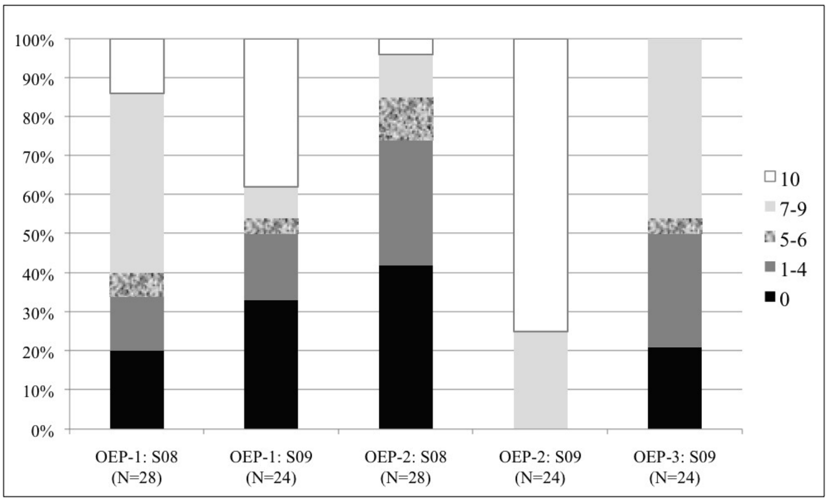

Fig. 4b. Student performance on Step 5 of the PSM in AE162.

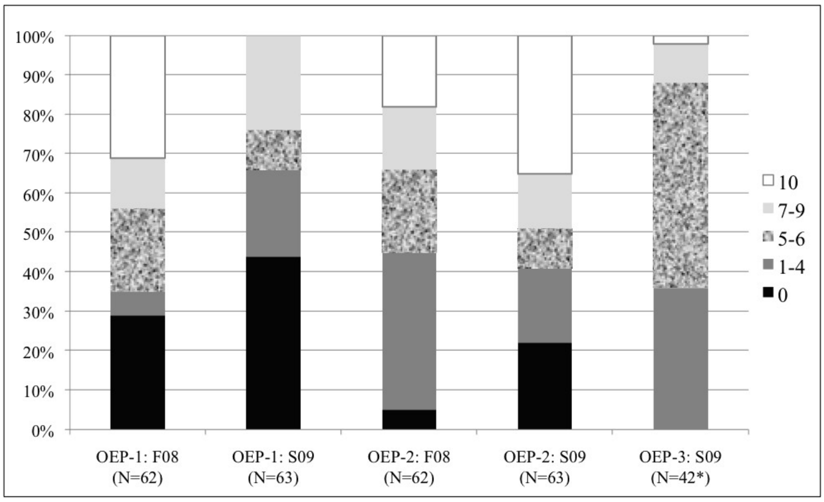

Fig. 5a. Student performance on Step 7 of the PSM in ME111.

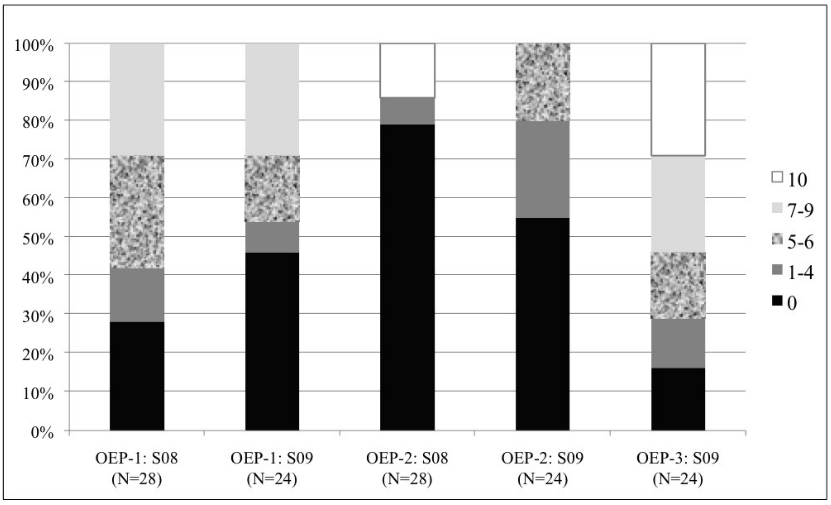

Fig. 5b. Student performance on Step 7 of the PSM in AE162.

the entire course and sometimes from more than one course was also identified as a major challenge. *'I was focused on using one equation instead of looking at the big picture'* one student said. Students come to realize that solving these problems requires *'solid knowledge of the material'* and *'there is no special section in the book to look for guidance'*.

While students pointed out the benefits of teamwork in tackling OEPs, they also identified working effectively in teams as a challenge. Coordinating meetings outside of class, dysfunctional teams, and agreeing on an approach to solve each problem were specific difficulties they mentioned. Yet they also came to realize that sometimes answers coming from their teammates 'may be different but still be correct'.

It is important to distinguish between cognitive and affective student difficulties in problem solving. The cognitive domain is concerned with intellectual outcomes, such as knowledge, understanding, and skills and typically carries most of the weight in engineering courses. On the other hand, the often-neglected affective domain involves emotional outcomes, such as interests, attitudes, and values. These are very important when considering some of the attributes needed for problem solving, such as, for example, willingness to risk and cope with ambiguity, welcoming change, and managing stress [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, even necessary, to solve some problems similar to the ones they have seen, it is also essential that students are given a sufficient number of OEPs, each with brand new context to practice application of first principles in their solutions.

On the other hand, some of the difficulties students experienced are affective, such as unwillingness to spend sufficient time on task, reluctance to write down ideas and create sketches while solving a problem, and being uncomfortable with ambiguity. As one student confessed in his reflection: *'If it requires extra research I will do it but reluctantly. I do not like having to do extra work, more than I need to get by. Part of this may be because I do not have a lot of time available to read and research'.* This comment reflects the attitudes of many SJSU students who are overwhelmed with work and family responsibilities yet take a full load of classes in hopes of completing their engineering degrees in four or five years. Affective skills as they relate to problem solving are further discussed in relation to Table 2 below.

6. STUDENT SUGGESTIONS TO HELP IMPROVE THEIR PROBLEM-SOLVING SKILLS

Students were asked to make anonymously specific suggestions for the instructor on how he can help improve their problem-solving skills. They were also asked to make specific suggestions for other students who try to solve OEPs. The following is a summary of their recommendations:

Suggestions for the instructor:

- 39% of the ME111 and 32% of the AE162 students felt that there was no need to change the way OEPs were introduced and problem-solving skills taught. Students wrote that *'the class is very interesting', 'problems are explained clearly', 'the guidelines are very structured', 'examples are covered very thoroughly',* and *'I like the way we did it!'.*
- 17% of the ME111 and 32% of the AE162 students suggested more in-class examples of how to solve OEPs.
- 15% of the ME111 students suggested more in-class discussion of the PSM, including more hints about each OEP. They would also like more opportunities to solve OEPs in class in small groups. Eleven percent (11%) of the ME111 students would also like more OEPs to be assigned as homework. *'I find them more meaningful than regular homework problems',* one student said.

Suggestions for other students:

- 24% of the ME111 and 14% of the AE162 students made suggestions related to time management: *'Start working on each problem early; don't try to do it all in one day!', 'give yourself time to study, understand, and visualize each problem'.*
- 19% of the students in both courses urged fellow students to *'follow the PSM and you will do just fine'. 'It helps a great deal in seeing what you have and where you need to go',* one student said. *'Think about the problem holistically, sketch and research before attempting any calculations'.* Another suggested *'first tackle problems in a way that makes sense to you, then follow the PSM to organize your ideas'.*
- *'Work with your team'* and *'find teammates you can work with'* was a suggestion made by 15% of the students in both courses. *'Don't be afraid to argue with your teammates'* but also *'listen to your teammates and be open to their views',* wrote one student. *'Different minds bring different ideas and knowledge to the table'*, said another.
- *'Talk to the instructor',* suggested 10% of the ME111 and 18% of the AE162 students. *'Ask for as much help as possible'.* On the balancing side a student urged to *'try to solve the problem by yourself first, without talking to anyone. Ask for help only when you can't figure out something'.*
- *'Keep an open mind and explore different approaches'* was a suggestion made by 10% of the students in both courses.

7. TRANSFERABLE SKILLS

Students were asked to identify what general skills, transferable to other courses or other situations, they learned in the process of solving OEPs.

- 37% of the ME111 and 27% of the AE162 students listed the ability to use the PSM as the most important transferable skill. They found the PSM to be *'very effective',* as it gave them *'a logical, systematic approach for solving problems', 'a scientific way of thinking',* and helped them to *'be organized'.* Furthermore, they stated that the PSM made it easier for them to *'reflect on their mistakes or weaknesses in the problem-solving process'.*
- Confidence in solving real-world problems was listed by 30% of the ME111 students. *'I can now look at real-world problems and apply basic principles to solve them',* said one student. Student confidence in their cognitive problem-solving skills is summarized in Table 1. A higher percentage of AE162 students declared confidence in the skills listed, compared with students in ME111. This demonstrates that it is possible to increase student confidence level with a systematic teaching of problem-solving skills in as few as two engineering courses.
- Making reasonable assumptions was a skill listed by 18% of the students in both courses.
- Team skills, such as ability to discuss a problem effectively and reach consensus, was listed by 10% of the students in both courses.

8. DISCUSSION

It is evident that no improvement in cognitive problem-solving skills can take place unless students bring with them the right attitudes and values when approaching OEPs (Table 2). For example, one must stay flexible while brainstorm-

Table 1a. Student confidence in their cognitive problem solving skills (ME111, N=54)

Indicate your level of confidence in each of the following:	I am very confident	I am somewhat confident	I am not at all confident
Following the PSM to solve OEP	30%	67%	3%
Following the PSM to solve well-defined problems (examples in the book, homework problems)	46%	50%	4%
Monitor my problem-solving process and reflect upon its effectiveness	20%	73%	7%
Draw upon my knowledge of the material when I solve practical, real world problems in new situations	20%	77%	3%
Use an approach that emphasizes fundamentals rather than trying to combine memorized sample solutions	20%	67%	13%

Table 1b. Student confidence in their cognitive problem solving skills (AE162, N=22)

Indicate your level of confidence in each of the following:	I am very confident	I am somewhat confident	I am not at all confident
Following the PSM to solve OEPs	18%	73%	9%
Following the PSM to solve well-defined problems (examples in the book, homework problems)	55%	45%	0
Monitor my problem-solving process and reflect upon its effectiveness	37%	59%	4%
Draw upon my knowledge of the material when I solve practical, real world problems in new situations	41%	55%	4%
Use an approach that emphasizes fundamentals rather than trying to combine memorized sample solutions	50%	50%	0

Table 2a. Student affective skills as they relate to problem solving (ME111, N=54)

Indicate how often you do each of the following when you solve problems:	Never/Rarely	Sometimes	Very often/ Always
I am more concerned about accuracy than speed	4%	46%	50%
I sketch a lot, write down ideas, and create charts / figures to help me visualize the problem	6%	50%	44%
I am organized and systematic	17%	39%	44%
I stay flexible (I keep my options open, I can view a situation from different perspectives)	10%	60%	30%
I am willing to take risks (try new things even though I am not be sure about the outcome)	16%	60%	24%
I cope well with ambiguity, welcoming change and managing stress	13%	63%	24%

Table 2b. Student affective skills as they relate to problem solving (AE162, N=22)

Indicate how often you do each of the following when you solve problems:	Never/Rarely	Sometimes	Very often/ Always
I am more concerned about accuracy than speed	0	36%	64%
I sketch a lot, write down ideas, and create charts / figures to help me visualize the problem	9%	55%	36%
I am organized and systematic	14%	64%	22%
I stay flexible (I keep my options open, I can view a situation from different perspectives)	14%	45%	41%
I am willing to take risks (try new things even though I am not be sure about the outcome)	14%	41%	45%
I cope well with ambiguity, welcoming change and managing stress	9%	73%	18%

ing possible ways to model a physical situation (Step 3) and value accuracy more than speed while implementing a mathematical model (Step 5). Needless to say being organized and systematic is a requirement throughout the PSM. With the exception of Step 1, which is entirely affective, the rest of the steps require a mix of affective and cognitive skills.

While grading the various OEPs in the two courses, it became apparent that lack of affective skills was a primary cause for low performance. The most common reason for a low score was a sloppy report with incomplete steps, indicating inadequate time spent on the problem. For example, in many cases where students set up and solved an incorrect model for a problem, they had failed to include necessary sketches in steps 2, 3, and 4. As a result they did not visualize the problem correctly. On the other hand, students who performed well were usually meticulous about completing each step of the PSM (i.e. they took time to research and read, explored various possibilities before settling on an approach, sketched a lot in their effort to visualize the problem, and presented everything they did in a clear, organized, and systematic way).

These observations suggest that affective skills facilitate the improvement of cognitive skill development. Clearly, the PSM reinforces students' affective skills by providing a way to be organized and systematic, as was reflected in several student comments above.

9. CONCLUSIONS

The analysis of the data collected in two upper-division engineering courses taught by the author shows that students encountered both cognitive and affective difficulties while solving OEPs. Top cognitive difficulties were (i) applying first principles in the solution of problems, (ii) reflecting on the problem-solving process, (iii) self-assessment of problem-solving skills (iv) defining a problem in engineering terms, (v) selecting a valid model for a problem (making appropriate assumptions), and (vi) following the PSM in its entirety. Top affective difficulties were (i) unwillingness to spend sufficient time on task, (ii) reluctance to write down ideas and create sketches while solving a problem, and (iii) dealing with ambiguity and uncertainty.

Adequate in-class demonstrations of what to do in each step of the PSM, practice with as many OEPs as possible, coaching, teamwork, time management, and the use of the PSM along with the rubrics presented in this paper seem to be effective means for overcoming the aforementioned difficulties for most students. The model presented in this paper was effective in increasing students' skills and confidence level in tackling OEPs.

Lastly and most importantly, it appears that affective skills facilitate cognitive skill development. This observation suggests that when teaching problem solving it pays to work first on student attitudes and values before emphasizing technical skills.

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APPENDIX— RUBRICS FOR ASSESSING STUDENT ENGAGEMENT AND EVALUATING STUDENT PERFORMANCE IN STEPS 2– 7 OF THE PSM

Table 3a. Rubric for measuring student engagement (Step 1 of the PSM) in ME111 (N=54)

How often have you done each of the following in connection with one of the OEPs or course project?	Never	1 or 2 times	3 to 5 times	More than 5 times
1. Asked questions related to an OEP during class	28%	56%	11%	5%
2. Contributed to a class discussion related to an OEP	30%	54%	13%	3%
3. Prepared two or more drafts of the solution of these problems before turning them in	7%	78%	11%	4%
4. Worked with classmates outside of class to prepare OEPs solutions	2%	37%	37%	24%
5. Helped other students with the solution of OEP	28%	41%	20%	11%
6. Used an electronic medium (listserv, chat group, Internet, instant messaging, etc.) to discuss the solutions of these problems	15%	50%	24%	11%
7. Used email to communicate with the course instructor regarding OEPs	77%	15%	4%	4%
8. Visited the course instructor in his office to discuss OEPs	35%	39%	19%	7%
9. Discussed ideas related to OEPs with others outside of class (students, family members, coworkers, etc.)	14%	54%	17%	15%

	Not at all interesting	So—so (lukewarm about it)	Very Interesting/ Engaging
10a. I found the 'soccer' problem:	5%	55%	40%
10b. I found the 'rain' problem:	4%	33%	63%
10c. I found my project*	2%	31%	44%

11. I worked harder than I normally do to solve the OEP in ME111	Never/Rarely	Sometimes	Very often
	5%	60%	35%

	# of hours	1–2	3–4	5–7	8–12	15–30
12a. I spent a total of ___ hours working on the ***soccer problem*** (alone, with my teammates, with the instructor) [*Average = 5.8 hours*]	# of students	17%	33%	24%	20%	6%
12b. I spent a total of ___ hours working on the ***rain problem*** (alone, with my teammates, with the instructor) [*Average = 6.6 hours*]	# of students	13%	30%	24%	22%	9%

13. How interested are you in learning the ME111 material?	Uninterested	So-so (lukewarm about it)	Very interested
	2%	35%	63%

14. How difficult is the course material for you?	Difficult	Average Difficulty	Easy
	54%	44%	2%

* Percentages do not add up to 100 because the project was optional.

Table 3b. Rubric for measuring student engagement (Step 1 of the PSM) in AE162 (N=22)

How often have you done each of the following in connection with one of the OEPs or course project?	Never	1 or 2 times	3 to 5 times	More than 5 times
1. Asked questions related to an OEP during class	22%	55%	14%	9%
2. Contributed to a class discussion related to an OEP	28%	41%	27%	4%
3. Prepared two or more drafts of the solution of these problems before turning them in	41%	36%	23%	0
4. Worked with classmates outside of class to prepare OEP solutions	14%	9%	36%	41%
5. Helped other students with the solution of OEP	23%	50%	18%	9%
6. Used an electronic medium (listserv, chat group, Internet, instant messaging, etc.) to discuss OEP solutions	32%	0	23%	45%
7. Used email to communicate with the course instructor regarding OEP	50%	19%	27%	4%
8. Visited the course instructor in his office to discuss OEP	28%	36%	27%	9%
9. Discussed ideas related to OEP with others outside of class (students, family members, coworkers, etc.)	46%	18%	18%	18%

10a. I found the *wing / tail* problem:	Not at all interesting	So—so (lukewarm about it)			Very Interesting/ Engaging	
	14%	68%			18%	
10b. I found my project	9%	50%			41%	
11. I worked harder than I normally do to solve the OEP in AE162	Never/Rarely	Sometimes			Very Often	
	4%	45%			46%	
12. I spent a total of ___ hours working on the *wing/tail* problem (alone, with my teammates, with the instructor) [*Average =6.6 hours*]	# of hours	1–2	3–4	5–7	8–12	15–30
	# of students	27%	14%	32%	14%	13%
13. How interested are you in learning the AE162 material?	Uninterested	So-so (lukewarm about it)			Very interested	
	0	14%			86%	
14. How difficult is the course material for you?	Difficult	Average Difficulty			Easy	
	32%	68%			0	

Table 4. Rubric for measuring student performance on Step 2 of the PSM

Score	Performance Criterion: Define one or more criteria (measures) for answering the question.
10	Identifies a proper ‘measure’. Includes appropriate sketches illustrating all relevant parameters.
7–9	Identifies a ‘measure’ that can indirectly lead to a more appropriate one. Sketches illustrate some of the relevant parameters.
5–6	Identifies 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.
1–4	Does not specify a useful ‘measure’ for the comparison. No sketches included.
0	Does not attempt.

Table 5. Rubric for measuring student performance on Step 3 of the PSM

Score	Performance Criterion: Generate appropriate questions related to the ‘measures’ you defined in Step 2, identify possible approaches (models) for solving the problem, and make reasonable assumptions.
10	Generates at least two relevant questions, identifies at least two different approaches, and makes all necessary assumptions for each approach.
7–9	Generates at least one relevant question, identifies at least two different approaches, and makes most of the necessary assumptions for each approach.
5–6	Generates at least one relevant question, identifies at least one approach, and makes most of the necessary assumptions for this approach.
1–4	Generates one or two relevant questions, does not identify an approach, does not make some or all of the necessary assumptions.
0	Does not attempt.

Table 6. Rubric for measuring student performance on Step 4 of the PSM

Score	Performance Criterion: Select an appropriate model for developing a solution, break down the problem into sub-problems, and determine what needs to be found in each sub-problem.
10	Selects the most appropriate model for developing a solution, breaks down the problem into appropriate sub-problems; provides complete list of what needs to be found in each sub-problem.
7–9	Selects an appropriate model for developing a solution, breaks down the problem into appropriate sub-problems; incomplete list of what needs to be found in each sub-problem.
5–6	Selected model for developing a solution is not described adequately; breakdown of problem into sub-problems is not appropriate or helpful; list of what needs to be found is incomplete.
1–4	Does not identify a model for developing a solution or does not break down the problem into sub-problems and / or does not list what needs to be found.
0	Does not attempt.

Table 7. Rubric for measuring student performance on Step 5 of the PSM

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.
10	All calculations are correct. Appropriate sketches, figures, and drawings included in the solution.
7–9	Most calculations are correct. Appropriate sketches, figures, and drawings included in the solution.
5–6	Some calculations are correct. Some sketches, figures, and drawings included in the solution.
1–4	Several of the calculations are incorrect. Important sketches, figures, and drawings are missing from the solution.
0	Does not attempt.

Table 8. Rubric for measuring student performance on Step 7 of the PSM

Score	Performance Criterion: *Discuss whether answer makes sense, evaluate appropriateness of models used and any assumptions made. Reflect on personal problem solving process.*
10	A. Comments on whether the answer is reasonable and why. Evaluates the appropriateness of any models used and any assumptions made.
	B. Reflects in depth on his/her personal problem solving process; identifies several strengths and several areas for improvement.
7–9	A. Comments on whether the answer is reasonable but does not explain why. Evaluates the appropriateness of any models used and some of the assumptions made.
	B. Reflects on the personal problem solving process. Identifies at least one strength and one area for improvement.
5–6	A. Comments on whether the answer is reasonable but does not explain why. Does not evaluate the appropriateness of any models used and/or some of the assumptions made.
	B. Inadequate reflection on the personal problem solving process. One strength and/or one area for improvement identified.
1–4	A. No comment on whether the answer is reasonable. No evaluation of the appropriateness of any models used and/or any assumptions made, based on the answer received.
	B. No reflection on the personal problem solving process. No strengths or areas for improvement identified.
0	Does not attempt.

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