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Engineering Problem Solving in Industrial Engineering Curriculum Reform

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Abstract

Problem solving is a major focus of the engineering profession, and upon graduation new engineers are faced with increasingly complex problems. Yet, existing engineering education practices often fall short in preparing students to tackle complex engineering problems that may be ambiguous, open-ended and ill-structured. In this paper, we describe a newly developed learning environment called the Engineering Learning Portal (ELP), which focuses on improving engineering problem solving throughout the industrial engineering curriculum. In the ELP, students are engaged in a structured process for solving unstructured problems while encouraging metacognitive activities, such as planning, monitoring, and evaluating. This helps students acquire the higher order cognition and integration of knowledge domains needed for effective engineering problem solving. In particular, a key element of the ELP is that it requires students to explain and evaluate their work while they are solving complex engineering problems. The underlying premise is that such metacognitive tasks are valuable to students because they eventually improve their engineering problem solving ability. We describe the ELP environment itself, our experience with implementing the environment in three industrial engineering classes, and how it has impacted engineering problem solving as part of the curriculum.

1. Introduction

Engineers are routinely faced with complex, ill-structured problems that differ dramatically from textbook problems routinely assigned in classroom environments. Such problems present many cognitive challenges, and a key element of the problem solving process is making decisions. Many decisions regarding the nature of the problem, the solution approach, and evaluation are made over the life of a problem scenario. These decisions are based on knowledge, perceptions, cognition, and negotiation. The resultant set of decisions should lead to a good solution if the underlying cognitive processes provide effective support for the decision making process.

Some problems encountered in engineering applications are easily recognized and have ready-made solutions that can be implemented by those with experience and the declarative and procedural knowledge of the scenario. The declarative knowledge describes the fundamental principles and facts relevant to the context. The procedural knowledge includes the methods and tools that exploit the declarative knowledge. Decisions for these types of problem are relatively simple to make as the expected outcome is well known. Once a student acquires experience with
these types of problems, relatively little learning occurs in these scenarios, amounting to incremental knowledge acquired from small perturbations of a problem context.

The more difficult engineering problems are open-ended, ambiguous, and ill-structured. Here the decisions become difficult because there is no direct experience in solving the problem. While procedural and declarative knowledge are helpful for various aspects of the problem, they are insufficient because the solutions are unknown. Learning is a major part of this type of problem as the participants must “learn as they go.” The issue dealt with in this paper is how students should be educated to deal with these kinds of problems.

For ill-structured problems the emphasis needs to shift to higher order cognitive skills and in particular metacognition. Metacognition refers to higher-order thinking that involves active control over the cognitive processes engaged in learning. Metacognitive processes may involve numerous activities such as, planning how to learn, monitoring one’s comprehension, and evaluating progress. The metacognition literature shows that students tend to be unaware of how well they are learning material, experiencing what Bjork (1999) described as illusions of comprehension. Cohen and Thompson (2001) recognized the need for reflection in critical thinking for ill-structured problem scenarios. Students often assume that whatever enhances performance in the short-term will enhance performance in the long-term, but in fact, circumstances that make initial acquisition more difficult may improve later performance. A focus on metacognition may fall into that category. Numerous studies have shown that good problem solvers (experts) differ from poor problem solvers (novices) in their use of metacognition. Although few studies have directly assessed whether the relationship is causal, the assumption is that as students become more aware of their own thinking and problem solving process and of the effectiveness of different strategies, their learning will be enhanced.

The above observations motivate a shift to teaching open-ended, ill-structured problems and also shifting the focus to students developing their metacognitive abilities. However, current pedagogies do not adequately address these learning needs. It would therefore be beneficial to have learning environment, or a learning management system that enables educators to effectively use more complex problem solving in the classroom. To be applicable to a variety of course and curricula, it is desirable that such a system be scenario based, where different modules can be based on various problems that arise in real applications, and can be solved using tools and techniques learned in different courses.

2. A Learning Management System for Engineering Problem Solving

A web-based Learning Management System (LMS) has numerous potential benefits for teaching engineering problem solving, but its design should reflect both the technical content and the learning objectives, so that the technology environment promotes learning that we value and effectively delivers the technical content. To increase its usefulness it should also be used to address challenges in the existing curriculum that may be difficult to solve without the enabling technology. As motivated above, it would be particularly useful to use information technology to develop a LMS that shifts the focus from well-structured homework problems to more realistic ill-structured problems, as well as emphasizing the higher-order cognitive skills associated with expert problem solving abilities.
In an effort to rethinking the entire industrial engineering curriculum, we are in the process of developing a web-based LMS where for each course students complete one or more modules that relate to the course content. These modules are designed to accomplish numerous goals identified as being desirable for engineering problem solving:

- Each module presents an ill-structured engineering problem that students must solve using the tools acquired during the course. This helps the students to not only make a connection between the course material and a real-world problem, but also develop their ability to apply discipline-specific knowledge to solve engineering problems and monitor their problem solving strategies.

- The modules are interconnected so that the relationships between previously isolated parts of the curriculum are made apparent. Over a set of several courses students will therefore develop a better appreciation of the connections among courses.

- The modules focus on helping students develop both their cognitive ability to structure problems and make decisions in industrial engineering knowledge domains and develop their metacognitive ability by reflecting on their solutions and justifying each action that is made.

For each module students must independently define goals, formulate problems, and develop solution strategies while mastering the course material. This environment is thus a fundamental shift from the existing emphasis on the traditional lecture format to active learning\textsuperscript{12,13}. This is also an ideal tool to encourage cooperation and communication with other students through collaborative learning\textsuperscript{19}.

One of the means by which technology can support learning is to present real-world problems as part of the curriculum and to create an active environment where students formulate and solve difficult problems using the tools learned in class\textsuperscript{4}. The new LMS is heavily centered on such realistic problems developed in cooperation with industry partners. Currently three modules have been implemented as part of the LMS for courses in engineering economy, manufacturing systems, and production systems. As additional modules are developed to link to the LMS, one of the key focus areas is the integration of the industrial engineering curriculum. The motivation behind this is that the traditional industrial engineering curriculum encompasses what may seem like loosely connected courses that address different elements of manufacturing and service enterprises. The engineering economy module is the first piece in a common web-based environment that will be used to integrate these courses, and at the same time encourage the development of specific learning skills. Thus, modules will deliberately highlight connections between the content of multiple courses. This will be achieved by such mechanisms as solving two closely related problems using material from two different courses and using the output of a module from one class as an input to a different module. This type of integration would be difficult to achieve without the use of the technology.

The fact that we are using information technology to achieve this integration of the curriculum also enhances a student's ability to solve engineering problems. In the past, and continuing to some extent for traditional engineering disciplines, foundational knowledge in mathematics and engineering sciences helped to integrate curricula as the concepts and tools introduced in the first two years were reinforced and expanded by their application in subsequent, discipline-specific
courses. For industrial engineering, we see information technology increasingly taking over this integrative function. However, the typical curriculum has not been revised sufficiently to allow the information technology we teach our freshmen to permeate the subsequent coursework. The key concept of this approach is a common learning environment based on new and emerging information technology tools and ideas that integrate isolated course content.

Another effective use of information technology to enhance learning is increased capacity for providing students with timely feedback, and to encourage reflection and revision on the part of the students. Using formative assessment for feedback and to encourage learning from mistakes is an integral part of this environment but has not yet been implemented as part of the engineering economy prototype module. However, special effort has been made to incorporate student reflection into the environment via student self-evaluations and explanations of actions. This is again something that is difficult to achieve without the enabling technology, and will be discussed next.

As has already been discussed in the introduction, educational psychology has recently had significant focus on metacognition as a key enabler to being a successful learner\textsuperscript{1,2,5,8,9,10,18}. Sometimes referred to simply as “thinking about thinking,” metacognition differs from just cognition it that it refers to higher order thinking that involves active control over the cognitive processes engaged in learning. This may involve numerous activities, such as planning how to learn a given task, monitoring one’s comprehension of the task, and evaluating the progress that is made towards the task.

Several researchers have recently focused on the application of metacognitive theory in education\textsuperscript{3,6,14,17,21}. It has been observed that as students become aware of their own thinking and problem solving process their learning can be enhanced. One of the key innovative elements of the new learning environment is a focus on the development of metacognitive skills. Thus, the several elements are incorporated into the modules that explicitly encourage students to reflect critically on their work, monitor their progress towards understanding the problem, planning the problem solving process, and evaluating their progress.

Throughout the project, students are required to provide a self-evaluation of their work based on the same rubrics that are used by the instructors to evaluate the final project. For example, before leaving the objective phase, where the students specify an objective function and the goal of their project, the students are prompted to evaluate the completeness, clarity, and justification of the objective. Thus, the IT is used to encourage student reflection and possibly revision based on this reflection. The standard for measuring the evaluation factors is made available to the students and they can be previewed at any time while the students are solving the problem. The purpose of the self-evaluation is to encourage students to reflect on their work and make revisions as necessary if it does not meet the set criteria.

In addition to the self-evaluations, students are required to explain and justify their actions throughout the module. For example, students must explain why they select their objective and why a specific task is included on the action plan. This is again intended to encourage students to be reflective and understand their own thought and problem solving processes. While providing justifications or explanations of actions is believed to be valuable in its own right, it also provides data that could be used for formative assessment. It is therefore of interest to
consider how predictive these explanations are of the final performance in solving the engineering problem.

Our experience from our pilot studies indicates that students are not accustomed to these types of reflections and in many cases gave either non-specific explanations or tried to go beyond what would be required for an explanation. We take this as an indication for the need to incorporate metacognitive skill development into the entire curriculum and expect as students move through such modules in a series of courses they will enhance their ability to reflect on their actions.

3. **The Engineering Learning Portal**

As described above, the thrust of the curriculum reform project described here focuses on a new Learning Management System (LMS) to improve the teaching of engineering problem-solving process based on real world industrial engineering problems. We call this LMS the Engineering Learning Portal (ELP), and it contains the modules and infrastructure used (1) to provide scenario specific information based on student-initiated requests, (2) to structure the problem-solving process, (3) to collect information on cognitive processes, (4) to collect work in multiple formats from each student team, and (5) to provide feedback to teams on their progress. After connecting to the ELP, students have access to specific information for a scenario. This information can take the form of reports, spreadsheets, design specifications, drawings, pictures, or streaming video. The problem-solving process is structured by the ELP into four stages.

- **Objective**: Students specify what they are trying to achieve before they begin the solution process and what measures they will use to evaluate their achievement of the objective. A justification of the objective is also required.

- **Plan**: Teams construct plans for solving the problem consisting of system actions (performed by the ELP) and student actions, which require the students to apply their knowledge of the domain implemented in the module. The team must justify each action in the plan.

- **Solution**: After completing the plan, students specify a solution based on a list of possible alternatives. A justification of the solution must be provided in order to submit the solution.

- **Performance**: A scenario-specific simulation model provides a representation of the system under the solution parameters selected by the team. Performance measures for the system are provided at pre-defined time periods. Students can use the results to modify their solution.

The ELP was designed to encourage the metacognitive processes of planning, reflecting, and evaluating one’s own progress (see Section 2.2). Along with each choice of objective, action and solution element, students enter a reason for making that choice. In order to progress from each of the first three stages, students must complete a self-evaluation based on rubrics. The evaluation criteria can be viewed prior to completing the stage. An example of the rubric to evaluate the objective phase is shown in Figure 1.
The problems in the ELP are deliberately kept open-ended as to better replicate real-world scenarios. Likewise, information is not simply given to students, but rather students can click on...
“Company” and then select from various departments, such as Operations, Manufacturing, and Purchasing. Figure 2 shows the view for the Engineering department. For each department, students can download relevant memos and other files, and when appropriate query relevant databases.

The first module of the ELP was developed for a course in engineering economic analysis. Engineering economy was determined to be a good choice for the first module for numerous reasons, but in particular because it has numerous connections to other courses in the industrial engineering curriculum. The problem scenario for the engineering economy module, developed in consultation with a local manufacturer, centered on the selection of a manufacturing strategy from three possible alternatives to implement in each of the next five years. In the Objective stage, students formulated and justified a numerical measure of performance they would later use to compare alternatives. The system actions available in the Plan stage consisted of gathering various types of information, along with optional studies that would result in costs and delays. The student actions were various types of computations and analysis relevant to the knowledge domain (see Figure 3 for an example).

Figure 3. Actions Phase for the IE 305 ELP module.

In the Solution stage, students specified a decision for each year. Completion of this step also required uploading an Excel spreadsheet with a net income and cash flow statement for the five-year horizon. Students could then progress to the Performance stage and view the results of a
simulation of the first year, including realizations of variables such as demand, production volume, costs and net income. After the first year, they could view the results of the market research study (if applicable) and modify the alternatives chosen for years 2 - 5. The simulation would run at this point, after which the students completed the final submission of their project.

Starting in Fall 2002, the first module has been tested extensively in our junior-level Engineering Economic Analysis course (IE 305). This is a 3-credit course required for industrial and electrical engineering majors, and a popular elective for mechanical and chemical engineers. Feedback from students was obtained through project self-evaluations, surveys, and focus groups. In addition, groups of students have been hired to evaluate the module. This feedback proved invaluable to revise module details, validate the learning environment, identify challenges and research issues, and to gain experience that will be leveraged for future module development.

During the Fall 2003 semester, a second module was also offered for the first time in IE 448 Manufacturing Systems. This is an upper-level course consisting primarily of IE majors. This module uses the same general setting as the IE 305 module, but has a different problem. In particular, the students are given the following problem statement:

With the explosion in demand since the reorganization of the company, Paragon has found the need to re-evaluate their original process of metal stamping of the sheet metal parts. They believe that current buying trends will continue at the same rate and thus exceed their ability to meet demand in their market niche. Their current inefficiencies with some of their processes need to be reviewed in light of their projected inability to meet this demand.

In response to the inability to meet demand, management has begun to investigate the feasibility and profitability of a number of alternative options. Possible metal cutting operations for sheet metal include:

- A new CNC turret punch press
- Die stamping operations
- Abrasive water jet
- Laser cutting
- Plasma cutting
- Oxy-fuel torch
- Wire electro-discharge machining
- Band saw

As before, the students must go through an objective, action, and solution phases. This new module allowed for the first effort to integrate course material. In particular, to select between the different cutting operations, students need to perform and economic analysis of each option. Thus, the output of the engineering economy module becomes an input to the manufacturing systems module and students more clearly see the connections between the two different courses.

The most recent module was developed for a course in Production Systems and was pilot tested during the Fall 2004 semester. The problem involved in this module involves new product
introduction for an international company. An interesting innovation added in this module is that the module is used jointly in a course at Iowa State University and the University of Strathclyde in Glasgow, Scotland. Each project team consists of two students from each university and the students must collaborate with each other to solve the problem. Adding such a global component is possible because the LMS is web-based and can be accessed from anywhere.

4. Understanding Student Problem Solving

The key goal of the ELP is to teach problem solving and decision making within the problem solving context. The approach taken by the ELP is two-fold. First, the ELP exposes students to more open-ended and ill-structured problems than students usually face as homework problem, and second the ELP explicitly encourages cognitive skills that have been found to characterize expert problem solvers, namely students’ metacognition. The latter is accomplished by asking students to evaluate their work by filling out the same rubrics that are used by the instructor for grading, and by providing explanations or justifications of key actions, which requires them to reflect on their work.

There are indications that the ELP does indeed enhance student problem solving. Direct evidence from students has been obtained both anecdotally and through focus groups. Such focus groups have been held both during and right after students complete the ELP modules, and during the focus groups students are asked about their problem solving process. While their approach to the problem solving varies and they offer various reactions, there are clear indications that they are being challenged to solve the problem. The open-ended and ill-structure format is particularly problematic to the students and many say that this “bothered” them, at least at first. Some students also explained that the format was different from what they are used to and it required them to find information for themselves. They described an “initial shock” to the format, and some students explained that it was difficult to remember where they saw information initially. In retrospect, it was good, but at the time, they had a different opinion. Students do seem to appreciate that there was not one way to do the problem, and enjoy the open-ended nature of the problem. More information on the results of these focus groups as well as other assessment can be found in Olafsson et al. (2004).

Further insights into student problem solving and how it relates to their metacognition can be obtained by considering the justifications students provide throughout the module. Students must explain why they select their objective (Phase 1), why specific tasks are included on the action plan (Phase 2), and why a particular solution is proposed (Phase 3). This is intended to encourage students to be reflective and understand their own thought process and how they are progressing towards solving the problem, that is, to engage their metacognition. Providing such justifications of actions has been found to be an integral part of learning problem solving for ill-structured problems. The explanations provided by students as they progress through the problem solving process are therefore important in their own right, but they also provide a rich source of data to better understand students’ reasoning.

Given that better problem solvers have better metacognition, our premise is that the explanations provided by the students provide a predictor of the success of the students as measured by the grades for both individual phases and the final grade for the project. It should therefore be possible to learn how to predict student grades based on the explanations. Furthermore, how
these predictions are made provides some insights into the cognitive process. By applying standard text mining techniques, we have verified this premise. The results show that students grades can be predicted with very high probability based on their justifications (over 95% accurate predictions), and more importantly that the most important part of the process is Phase 1, where students formulate their objective.

The text mining analysis of the ELP data from the engineering economy module described above is reported in detail in Olafsson (2005). It is interesting that some very simple rules can be induced that have high predictive accuracy. An example of this is the following:

If the Phase 1 explanation includes none of the following terms: determining, minimum, problem, compared, product, reliable, business, financed, plan, crucial, indicate, ability, implement, and effective, then the grade will be low; otherwise it will be not low.

This rule turns out to have an estimated accuracy of 94% for predicting which students obtain low grades, defined as being in the lowest quartile, versus not low. Interesting results are also obtained by considering which words used in student explanations are the most predictive of success in solving the problem. The most predictive words for the rubric grade for each phase of the ELP individually are reported in Table 1. Considering these words, it appears that relatively few of those words are technical terms related to engineering economy, but more describe the problem solving process itself.

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
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<tbody>
<tr>
<td>benefit</td>
<td>analysis</td>
<td>change</td>
</tr>
<tr>
<td>calculate</td>
<td>depreciation</td>
<td>cheapest</td>
</tr>
<tr>
<td>compared</td>
<td>different</td>
<td>continued</td>
</tr>
<tr>
<td>evaluate</td>
<td>gathered</td>
<td>demands</td>
</tr>
<tr>
<td>examining</td>
<td>order</td>
<td>handled</td>
</tr>
<tr>
<td>financed</td>
<td>percentages</td>
<td>justify</td>
</tr>
<tr>
<td>lost</td>
<td>project</td>
<td>operating</td>
</tr>
<tr>
<td>proceed</td>
<td>solution</td>
<td>time</td>
</tr>
<tr>
<td>process</td>
<td>table</td>
<td>utilized</td>
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<td>profit</td>
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The results from the text mining show that the student explanations are very predictive of performance, from which we infer that there does indeed appear to be link between how well students perform in solving ill-structured engineering problems and the metacognitive abilities that are reflected in the explanations.

6. Summary and Future Work

Engineering problem solving is a critical skill but one that is difficult to teach in a classroom setting. The Engineering Learning Portal (ELP) has been developed as part of a curriculum
reform effort that aims to introduce problem solving for ill-structured problem into every course of the industrial engineering curriculum.

We described the motivation behind the ELP, the structure of the environment, and the three modules that have been developed so far. One of the interesting elements of the ELP is its direct focus on metacognitive development by requiring students to provide evaluation (through rubrics) and reflection (through explanations) of their work. We also reported how these explanations are very predictive of student performance, providing additional evidence of the link between problem solving and metacognitive abilities.

Future work will continue to develop additional modules for the ELP. We also plan to further refine the models that predict performance based on explanation and incorporate those into the ELP to provide formative assessment of student performance. Finally, we are looking at how to model the problem solving process itself using problem space theory and how to use data mining to help us understand both the states and the transitions in the problem space.

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Bibliography


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