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Developing Professional Competencies through Challenge to Project Experiences*

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Industry can contribute significantly toward a dynamic engineering curriculum. A major theme in the industry-based dialogue with universities is that engineering graduates need to improve their professional skills; including written proficiencies, oral communication expertise, and teamwork skills. The authors have redesigned a course that combines water and wastewater treatment into a challenge-based instruction that develops both the students' conceptual and professional competences associated with civil engineering. The university joined with an industry partner to use their existing facility as an anchor for challenge-based learning activity. Opportunities for students to demonstrate and practice professional skills were extensively integrated into the design experience. While challenge-based instruction concepts are by no means new, the principles have not previously found widespread application within the civil engineering discipline. The objective of this study was to investigate student experiences for learning both content and professional competencies within a wastewater treatment course. A major finding of this study is that the traditional lecture style course could be redesigned in a manner that develops students' expectation of what it means to be a professional and the skills associated with that, while at the same time advancing their knowledge of wastewater treatment. The students self-reported that the most significant aspects of the learning experience were those related to their professional competencies. Those particular learning experiences relate directly to the skills requested by industry.

Keywords: professional competencies; challenge-based instruction; problem-based learning; learning cycle; STAR Legacy

INTRODUCTION

Responding to industry's request for professional skills

MANY FACTORS contribute to the continuously changing landscape of engineering education. Educators iteratively refine the engineering curriculum to better prepare their graduates to meet the demands of the industries and the research institutions they join. Prados [1] identified five major drivers that shape the engineering curriculum and define desired outcomes for engineering graduates. These organizations include:

- Industry—Through such connections as advisory boards and alumni surveys.
- Professional Societies—Publications and conferences related to the mission statement of organizations including the American Society for Engineering Education (ASEE) and the Education Society of IEEE (formerly the Institute of Electrical and Electronics Engineers).
- Private Foundations—Organizations such as the F. W. Olin Foundation, Whitaker Foundation, and Sloan Foundations.
- The National Science Foundation—Providing funding for research and offering direction to various engineering education programs.
- ABET (formerly the Accreditation Board for Engineering and Technology)—By defining and implementing accreditation requirements.

Industry feedback on graduate performance remains an invaluable and timely source of information. Industry surveys are used on a regular basis to evaluate the perceived competencies of engineering graduates. In general the results of these surveys indicate that engineering graduates, in the United States, are receiving a solid technical education, but they lack other desired professional skills. Industry also plays a role in assisting ABET in defining the required competencies of engineering graduates, which ABET integrated in the Criterion 3a–k (Engineering Criteria 2000). Todd, Sorensen, and Magleby [2] report similar results from a nationwide (United States) survey on industry perceptions of the weakness exhibited by

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engineering graduates. Included in their reported list are:

- lack of design capability or creativity,
- lack of appreciation for considering alternatives,
- poor perception of the overall engineering process,
- weak communications skills, and
- little skill or experience with working in teams.

Accordingly, many of the desired graduate competencies identified in the survey reported by Todd *et al.* [2] are echoed in the Engineering Criteria 2000 (EC 2000). With the launch of EC 2000, substantial attention has been given to methods of integrating and assessing the outcomes-based requirements of Criterion 3a–k. Also, Felder and Brent [3] note that a common complaint is that 'graduates cannot write a coherent report or give a comprehensible talk', however, 'we clearly have not yet worked out how to raise those skills to satisfactory levels.' While at the same time McMasters [4] states that, from an industry perspective, professional skills are a cornerstone of a 'well-rounded engineering' for the 21st century. Many academicians have struggled to identify approaches to implementing the Criterion 3 Outcomes into what appears to be an already overcrowded engineering curriculum.

New pedagogical models for instruction provide methods for developing engineering competencies, professional skills, and professional identity (Brophy, in review). In this paper the authors report on a 'problem-based learning' experience integrated into a wastewater treatment course with the specific intent of addressing industrial perceptions as identified by Todd, et al. [2], as well as several of the Criterion 3 Outcomes. Specifically, the authors designed a learning experience that provides students with opportunities and information to evaluate and design complex processes for wastewater treatment and to effectively communicate their designs. The students are then poised to persuade a client that their design is best for the client's situation.

The authors begin this paper with a short description of the theoretical perspectives guiding our design for effective learning environments. Then the methods and results of this descriptive research study are presented. The last section identified the implication of this study for designing similar learning experiences and considerations for a comparison study to evaluate student learning with a challenge-based instruction environment versus traditional instruction.

Generative learning environments

Many engineering classrooms are adapting pedagogical methods founded on constructivist's theories of knowing. These theories suggest that learners must be actively engaged in acquiring and refining their understanding of concepts and how to use this knowledge in various settings. Research on effective learning environments indicate that learners are better prepared for future learning experiences when they engage in learning activities that encourage them to articulate or demonstrate what they know and refine their thinking through self guided learning activities, interactions with their peers and instructors. A general framework called *How People Learn (HPL)* [5] describes four general dimensions of effective learning environments observed in K-12 education. The framework emphasizes the importance of not only centering on the formalism of the knowledge to be learned, but also on factors centering on the learner, how they learn the specific content, assessments (both formative and summative) and issues of community (e.g. in undergraduate education this could include the classroom, department, university and specific profession).

Many models of problem-based learning environments blend these dimensions into their instructional methods. For example, Barrows [6] defines taxonomy of principles used for medical instruction designed to improve clinical skills. Williams [7] expands on this to compare and contrast PBL in medicine with Case-Based Reasoning used in law. Anchored inquiry environments have been used in middle school math and science, instruction [8], educational psychology, and bioengineering [9]. Prince and Felder [10] define inductive learning environments that are emerging in engineering education for developing engineering problem solving abilities.

The general instructional design principles governing problem-based learning are:

- to provide an accessible context for knowing (conditions of when and how to use the knowledge);
- to encourage reflection, refine and reapplication of knowledge;
- continual testing of knowledge (formative assessment) and provide formative feedback; and
- to encourage synthesis and integration of ideas in multiple and similar contexts.

Felder and Brent [3] believe 'the instructional method known as problem-based learning (PBL) can easily be adapted to address all eleven outcomes of Criterion 3.'

The authors selected to use a 'problem to project' based approach to problem based learning. That is, instruction begins with the presentation of a term project as a culminating event for the students' learning. Within Mailicky, Lord, and Huang's [11] pedagogy decision matrix, this form of active pedagogy is defined as 'project-based learning' (PjBL). The scale of the project requires a number of sub-problems that become themes for an individual inquiry and didactic lectures. The learning environment for exploring these sub-problems, or what the authors refer to as challenges, can leverage principles and guidelines from challenge based instruction [12–14]. These sequences of challenge support learners self guided inquiry into solving the larger project goals, which the authors refer to as the Grand Challenge. The following outlines the learning theory associated with challenge based instruction.

STAR Legacy Cycle

The authors have adopted the STAR Legacy Cycle [12] as the learning cycle used for challenge-based instruction, as a framework for organizing our instructional design for an undergraduate course in wastewater treatment. The learning cycle shown in Fig. 1 engages learners in a process of inquiry around a complex challenge. The initial phase begins with the presentation of a challenge in terms that the target learning population can comprehend and have some intuitions on how to approach a solution. They use their prior knowledge to 'generate ideas' regarding what they think is important about the challenge, how they might solve the problem and questions about what more they need to learn. Then they compare and contrast their ideas with 'Multiple perspectives' provided by others who are knowledgeable about the issues and concepts relevant to the challenge. These initial steps help students identify what they know and what they need to learn, which primes them to enter a phase of 'Research and Revise'. Research and Revise activities include everything from hands-on activities to didactic lectures as methods to help students develop conceptual understanding of the concepts related to the challenge. 'Test your mettle' are formative assessment activities linked with research and revise activities that provide learners feedback on their progress. The final 'Go Public' phase requires learners to integrate the knowledge they have gained to either solve the original challenge or a similar challenge.

In the water and wastewater treatment course the STAR.Legacy model was organized around a Grand Challenge to evaluate various options for redesigning an industrial wastewater treatment process. The STAR Legacy Cycle has been implemented in a variety of disciplines [7–10], but research indicates limited prior application within civil engineering. Students were given a 'reflection notebook' (or design notebook) that they used to record their initial thoughts about this challenge and the evolution of their ideas as they progressed through learning activities throughout the semester. The 'Research and Revise' activities for this Grand Challenge consisted of a series of smaller challenges linked to sub-processes associated with the Grand Challenge. Prior to the start of class, students were given a topic to consider and asked to generate ideas about the topic in their reflection notebooks. In some cases guest lectures were present to provide multiple perspectives on the case. Lectures were given to explain the major concepts relevant to the assigned challenge and provide students with the framework to solve various computational and analysis problems. In some situations interactive classroom activities were implemented such as small group problem solving and discussions so that students could explore the ideas, receive feedback on their thinking and ask questions of the instructor. Written homework assignments were used to help students apply their knowledge and subsequently receive feedback on their level of understanding.

The 'Go Public' activity for the Grand Challenge consisted of a written group report and group presentation. Students synthesized their ideas to support their argument for proposing a particular method for redesigning the wastewater treatment process. They were evaluated on content and technical analysis of their redesign, the professional quality of their presentation and their ability to respond to 'what-if' situations relevant to their proposed design.

A more detailed description of the actual activities is reported in the methods section.

Objectives of this study

The authors expected to define an efficient method of integrating professional skills into challenge based instruction with minimal potential administrative overhead. Generative learning activities associated with the Learning Cycle were used at each phase to enhance the students' ability to evaluate and design wastewater treatment systems and predict system performance. While the primary learning goals for the course were relevant to water and wastewater treatment, secondary learning goals were related to the survey results reported by Todd *et al.* [2] and the ABET Criterion 3 Outcomes. Specifically, learners were expected to be able to identify alternative design considerations for wastewater, perform appropriate computations to justify their results, and effectively communicate their design decision in an effort to persuade a customer of its validity as an appropriate (and optimal) solution to their current needs.

The authors anticipated several outcomes. First, it was hypothesized that students will demonstrate increased knowledge of wastewater treatment as a

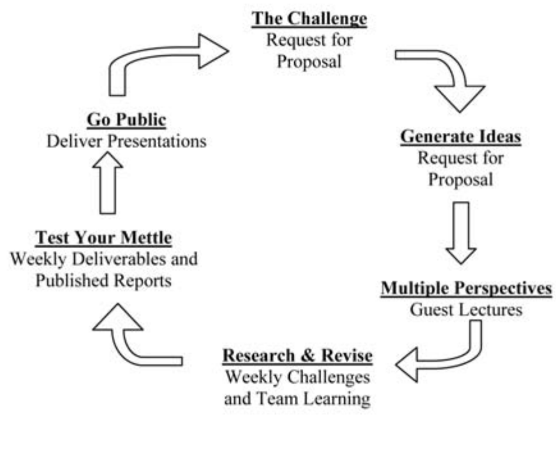

Fig. 1. The STAR.Legacy Cycle. Adapted from the VaNTH Engineering Research Center in Biomedical Engineering Technologies (http://www.vanth.org).

result of the innovative learning methods. Second, students will perceive that they learned more (depth and breadth) wastewater treatment knowledge via the PBL and CBI methods than by traditional lecture methods used earlier in the course. Next, students will report a preference for engaging in the generative learning methods used throughout the second half of the course. Finally, students will perceive an increase in written and oral communications skills, as well as teamwork skills as a result of the PBL experience.

METHODS

The Purdue University water and wastewater treatment course (CE456) is an upper-level, undergraduate technical elective that is also offered for graduate credit (with additional requirements). The Purdue course catalog describes the class as:

> Fundamental concepts and design procedures for the treatment of municipal and industrial wastewaters. Problem assessment; determination of effluent quality; preliminary treatment; biological, physical, and chemical treatment methods; and utilization and disposal of residues [13].

The full-semester course provides students with the fundamental design principles of both water and wastewater treatment. The CE456 course, like many traditional engineering courses, has been instructed using what Raju and Sankar [16] described as 'teaching by telling' methods that lead to 'long periods of uninterrupted instructor-center, expository discourse, relegating students to the role of passive spectators in the classroom.'

Course content was separated such that roughly seven weeks of instruction focused on water treatment design, followed by wastewater treatment during the remainder of the semester, approximately 8 weeks. The water treatment design content was delivered using only traditional instruction methodologies. Conversely, the wastewater treatment content was delivered utilizing the CBI and PBL principles.

In the fall of 2006, fifteen students registered for the CE456 course. Eight of the students were pursuing a bachelor's degree in Civil Engineering, six were pursuing a master's degree, and one was pursuing a doctorate degree. Four of the students were female and five of the students held international status. The CE456 class is not a senior design or capstone course.

Applied problem-based learning

One of the suggested principles of PBL is that the 'problem' should be authentic in nature [4, 11]. A major pharmaceutical company, located in proximity to West Lafayette, Indiana, has held a long standing relationship of collaborative educational and research activities with Purdue University. The pharmaceutical company graciously offered to act as a corporate partner for the PBL experience. Specifically, the company owns and operates an industrial wastewater treatment facility. The treatment facility is oversized for the current volume of manufacturing conducted at the plant. Accordingly, the PBL experience was designed around the goal of evaluating the existing treatment facility and considering options for altering the facility. The pharmaceutical company took an active role in defining the problem statement such that it addressed real issues.

In keeping with the principles of PBL and the concept of integrating professional skills, the project was designed to appear authentic by simulating a typical industrial practice of responding to a Request For Proposal (RFP). The RFP was designed to appear as if the pharmaceutical company was soliciting assistance from a group of fictitious consulting companies. The RFP contained traditional information, including a discussion of the facility, identification of project goals, a listing of possible design alternatives, and extensive data about the operation of the facility. The RFP also established the ambitions of the pharmaceutical company to adhere to ethical and environmentally sound practices. Finally, the RFP also included an eight week schedule that identified daily activities and delivery deadlines for the PBL activities.

The students enrolled in the course were organized into consulting companies competing for the project. Students were assigned to consulting companies rather than allowing them to self-assemble. An attempt was made to create a mix of students in each company, relative to graduate/undergraduate status, gender, and national/international status. Ultimately, three teams of four students and one team of three students were created. The consulting company concept permitted students to work together on project deliverables and required development and utilization of teamwork skills. During the early portion of the project, each consulting company received individual coaching from the instructors on methods of developing teamwork skills. The consulting company scenario also created a sense of competition in the classroom. The class, as a whole was reminded at several points during the project that they were all in the learning process together, but each consulting company developed its own approach and documentation to respond to the RFP. Ultimately, the competition was artificial in nature, as the companies were not truly competing for course grades.

Applied challenge-based instruction

A project and challenge based approach was used to organize the learning experience and assessments for this course. The RFP was presented as a Grand Challenge (term project) as part of the wastewater treatment portion of the course. Addressing the Grand Challenge required the students to evaluate three alternatives for modifying the existing wastewater treatment facility, as detailed in the RFP. Each team has a specific alternative (or unique grand challenge) to pursue that included a need to compare and contrast their alternative with the other modification plans. In addition to addressing the requirements and alternatives presented in the RFP, consulting companies were encouraged to develop creative alternatives not identified in the RFP. As a team, each consulting company was obligated to prepare a formal report that included a discussion of alternatives, considerations used in evaluating the alternatives, decision model employed, and well defended recommendations. Formal reports were addressed to a point of contact at the pharmaceutical company. Students received instruction on formulating design considerations, such as economic assessments, environmental impacts, long-term maintenance, and fluctuations in plant production. Students also received instruction on methods of formulating a decision model.

A second component of the Grand Challenge required each consulting company to prepare and deliver a formal presentation that defined and supported its design recommendations. This part of the challenge was equated to a 'short-list' presentation as performed in consulting practice. For the purposes of the course, all the consulting companies made the 'short-list' and thus, were required to make their presentation to the perspective client (pharmaceutical company). Formal presentations, lasting 20 minutes, were made by each consulting company to the course instructors and a contingent of employees from the pharmaceutical company. Consulting companies were evaluated based on the technical content of their presentations, ability to talk beyond the prepared presentation, confidence, public speaking aptitude, and professional demeanor. Companies were also evaluated based on their ability to address technical questions raised by the instructors and representatives of the pharmaceutical company.

In addition to the Grand Challenge, Weekly Challenges were developed to evaluate student learning on a 'weekly' basis; with most having a submittal time of less than one week. Weekly Challenges were designed to test broad knowledge of concepts, as well as student ability to perform content specific calculations. Students were required to utilize multiple resources (more than just class notes and their text) to fully address the challenge questions. Many of the Weekly Challenge questions required students to synthesize the data provided in the RFP. Students worked in their company groups to prepare professional deliverables for each of the Weekly Challenges.

Driving questions were presented before each lesson to set the context and conditions for applying the information presented in the lectures. Following the STAR.Legacy framework, learners generated ideas in their notebooks about the challenges and questions about what more they needed to learn. They were then given resources in which to Research these ideas and Revise their conception of how to apply the new information to their Grand Challenge. These resources included traditional lecture, guest lectures, and classroom and team discussions. The Weekly Challenges were designed around learning objectives for the primary lecture sessions. Each set of lectures were related to the individual processes that contribute to an overall wastewater treatment system. The lectures were delivered to the students in the order that they would be encountered in a wastewater treatment facility (influent to effluent). Students 'tested their mettle' by submitting their final responses to the Weekly Challenge and receiving feedback much like a traditional homework assignment.

Completion of the Weekly Challenges contributed to the ability of the consulting companies to effectively address the Grand Challenge. However, substantial, self guided, additional work was required to complete the Grand Challenge.

Integrated professional competencies

The PBL and CBI instruction are designed to develop both students knowledge of wastewater treatment and practice professional skills. Specifically the authors targeted teamwork and written and oral presentation of ideas. We clearly identified these objectives as part of the course learning objectives.

As noted previously, the primary learning objectives of this PBL were related to wastewater treatment knowledge. However, the secondary learning objectives included the incorporation of activities to improve and practice professional skills. Professional competency activities were integrated throughout the PBL. Table 1 identifies specific course components and associated non-wastewater treatment competencies.

The Weekly Challenges required teamwork and

Table 1. Non-wastewater treatment competency outcomes from course components

Course component	**Non-wastewater treatment competencies**
Grand Challenge—Report	Written Communication, Teamwork
Grand Challenge—Presentation	Oral Communication, Teamwork
Weekly Challenges	Written Communication, Teamwork
Oral Defense	Oral Communication, Consideration of Alternatives
Reflection Notebooks	Metacognition
Company Structured Teams	Teamwork, Awareness of Business Practices
Request for Proposal	Awareness of Business Practices, Consideration of Alternatives
Guest Lectures	Awareness of Business Practices, Consideration of Alternatives

written communication skills to prepare a deliverable on an intentionally aggressive schedule. The Weekly Challenges commonly included open-ended questions requiring the consulting companies to prepare and defend a response. Weekly Challenges were graded on not only technical correctness, but professional presentation, as well.

Completion of the Grand Challenge report requires students to exercise significant teamwork skills to accomplish all the requirements of the RFP and prepare a formal document on a tight schedule. Professionalism of the report, as defined to include report formatting, presentation style, and appropriateness of supporting figures, tables, and appendices, was a substantial part of the grading rubric.

Team presentation of the Grand Challenge was one test of teamwork and oral communication skills. The oral defense given by each student tested individual oral communication skills as he or she attempted to effectively discuss their thoughts in response to question asked by the panel.

Metacognition

Each student was provided with a composition notebook at the start of the PBL to record their ideas related to the Weekly Challenges and to write about their experiences with the PBL. Students were also encouraged to use the notebook to record their thoughts and ideas about the project beyond the structured, in-class writing activities. The intent of the notebooks was to encourage the students to think about their own learning (metacognition). This type of reflective practice is an important component of design [17], but is not typically used as part of undergraduate education.

Instructors

Three instructors were involved with the design and implementation of the PBL. The lead instructor for the course has over 20 years of teaching experience and has previously delivered water and wastewater treatment courses at many universities. The lead instructor delivered the water treatment lectures (first seven weeks of the semester) using traditional instructional techniques. Further, the lead instructor contributed to the PBL design and participated in the assessment activities, but did not deliver the wastewater treatment lectures. The wastewater treatment lectures were prepared and delivered by a secondary instructor who recently completed a Ph.D. in Civil Engineering and had considerable wastewater treatment background. The final member of the instruction team has eight years of consulting engineering experience, four years of adjunct teaching experience, and is pursuing a Ph.D. in Engineering Education at Purdue University.

Three guest lectures were delivered during the PBL. As discussed previously, the STAR.Legacy Learning Cycle uses multiple perspectives as a resource to help students actively make links between their own learning goals by leveraging the use of analogous cases to identify relevant knowledge they may need. Guest lectures included a representative from the pharmaceutical company, an individual performing research in the wastewater arena, and a team of engineers from a wastewater treatment design consulting company. The guest lectures provided the students with first-hand perspectives as complements to the experiences delivered by the primary instructors. Specifically, the pharmaceutical representative provided the perspective of the 'client' as both the owner and operator of the treatment facility under review as part of the PBL. The individual performing wastewater-based research discussed the process of identifying stake-holders, design considerations, and defining a decision making model. Finally, the representatives of the consulting company discussed the process it performs in preparing a design and making professional presentations to clients.

A unique aspect of PBL is that the instructor(s) must often assume the roles of facilitator, coordinator, or coach to enable the students to advance their own knowledge within the team setting [11]. This course specific PBL included lectures during roughly half of the schedule meeting times. Thus, this experience did not fully rely on student learning within small groups as Bransford, *et al.* [4] might suggest.

All three instructors collaborated throughout the PBL to record and compare observations of student activities and possible evidence of learning. The Results section of this paper includes reference to observations made by the instructors.

Methods of learning assessment

Several assessment methods were used to provide formative assessment to the students on their progress toward the learning objectives and summative assessments of their overall project performance on wastewater treatment methods. The Weekly Challenges and Grand Challenge (report and presentation) were collected and graded in accordance with a rubric that the students assisted in defining. Permitting the students the opportunity to contribute to the grading rubric helped them think about their own criteria for success. Two other assessments were used as part of the evaluation of the instruction on the last eight weeks of the course that used the PBL and CBI approach to instruction.

A pre-assessment measured students' ability to sequence the major stages of a wastewater treatment process on the first day of the PBL module. Students were presented with a flow diagram consisting of multiple boxes randomly arranged around a single page. Each box was labeled with the name of a unique and discrete process within an industrial wastewater treatment facility. On an individual basis, the students were asked to use arrows to connect the boxes in the order that the processes would be encountered (influent to effluent) in a treatment facility, thereby completing the flow diagram. The use of this pre-assessment allowed the course instructors to evaluate pre-existing student knowledge of wastewater treatment at the start of the PBL. This pre-assessment experience had the potential for providing students with a system overview of the concepts they will be exploring, helped them assess what they currently know, and generated questions about what more they need to learn as part of the following CBI instruction. Therefore, the authors view this pre-assessment as an integral portion of the instructional process. However, students did not receive direct feedback on their performance on this assessment. They are obligated to actively integrate the information provided during instruction to refine their understanding of the system overview. Students were asked to complete the same flow diagram near the end of the PBL as a post-assessment tool.

The final assessment employed during the PBL was an oral defense that each student performed on an individual basis. Each oral defense lasted approximately 10 minutes and was performed in a closed environment. The student and the instructors were the only individuals present during this assessment. Each student in the course was asked to respond to a list of questions prepared by the instructors. The open-ended questions were designed to evaluate the student's knowledge of wastewater treatment. Each student acted as a representative of their consulting company and was asked to discuss the alternatives presented in the RFP and the recommendations made by their consulting company. Students were asked to defend their company's recommendation or discuss why they personally feel their company may have proposed the wrong design recommendation. Two of the three course instructors graded student performance during the oral defense based on pre-established criteria.

An exit survey was designed and administered to capture the students' experiences with the PBL. The survey was designed to evaluate students' perceptions of the problem-based learning experience and how it contributed to their learning. The survey was administered in paper format. Students completed the survey on a voluntary basis during their final course meeting and after all institutional course assessment tools were complete.

RESULTS OF EXIT SURVEY

The exit survey results were assembled into common groups and are presented graphically below. In the case where a range of responses were possible, the data were analyzed by assigning numeric values across the range (e.g. strongly disagree = –2, disagree = –1, agree = 1, and strongly agree = 2). Rather than presenting numerical values, descriptions have been substituted on the figures where appropriate. However, it should be noted that the graphic presentation assumes an even distribution between each response value.

Wastewater treatment knowledge

The primary objective of the CE456 course is to develop students' abilities to critically evaluate design decisions associated with water and wastewater treatment. The focus of the PBL was the wastewater treatment portion of the course and had the added instructional goals of synthesizing evidence to justify a design and successfully present this argument to a client.

The exit survey provided the students with the opportunity to evaluate their own knowledge of wastewater treatment prior to and after completion of the PBL. Figure 2 illustrates the results of that inquiry (survey Questions 1 and 2). The results indicate that the students reported a wide range of perceived initial knowledge. In contrast, at the end

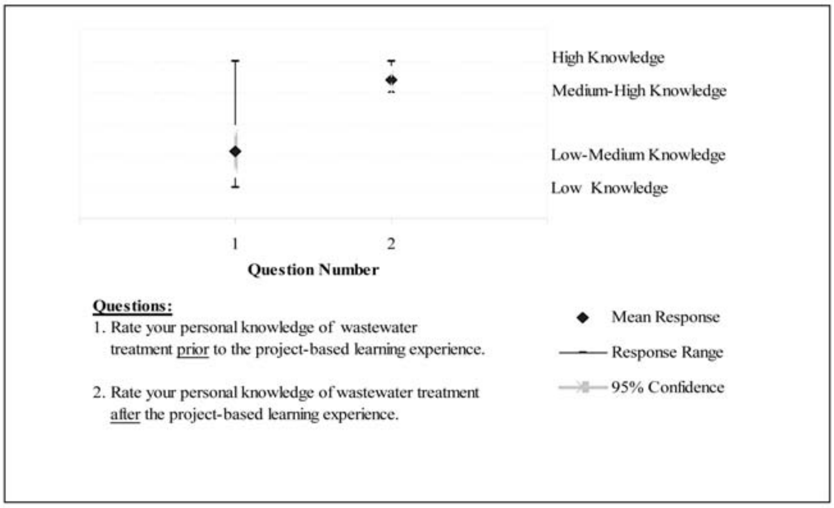

Fig. 2. Student perceptions of wastewater treatment knowledge prior to and after the project-based learning experience: mean response, response range, and 95% confidence interval.

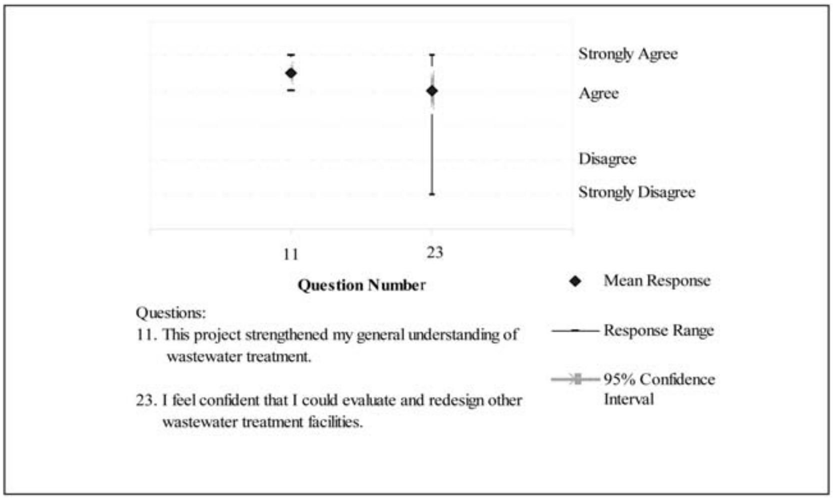

Fig. 3. Student perceptions of wastewater treatment knowledge resulting from project experience and ability to transfer knowledge: mean response, response range, and 95% confidence interval.

of the PBL, the students consistently rated their knowledge as 'High' or 'Medium-High.' The results also indicate an increase in average perceived knowledge.

Figure 3 illustrates the results of Questions 11 and 23 of the exit survey, which also allowed the students to assess their knowledge of wastewater treatment and the ability to transfer that knowledge to other wastewater problems. The results of Question 11 (Fig. 3) appear to reinforce the students' perceived knowledge indicated in Question 2 (Fig. 2). However, the results of Question 23 appear to indicate that while the class on average felt they could transfer the knowledge, there was a large range in the reported confidence to do so.

An informal question posed to each student during the oral defense period asked if they would be more comfortable approaching a water treatment design problem or a wastewater treatment design problem. Ten of the fifteen students stated that, based on their experiences during the CE456 course, they would feel more comfortable with a wastewater treatment problem. Three of the students said they would prefer a water treatment problem and the remaining two said they would feel comfortable with both.

Major activities contributions to learning

The authors anticipated that several critical activities contributed to the constructivist's theories of knowing because they engaged learners in actively applying what they know and reflect on this knowledge. Therefore, the exit survey allowed the CE456 students to rank order six items relative to the contribution each item made to advance their learning. The six PBL activities selected included a tour of the pharmaceutical wastewater treatment facility, presentations made by the guest lecturers, consulting (team) presentations, consulting (team) reports, notebook reflections, and individual oral defenses. The computed averages indicate that the students believe that the team presentation and the team report contributed the most to their learning (Fig. 4). These data were

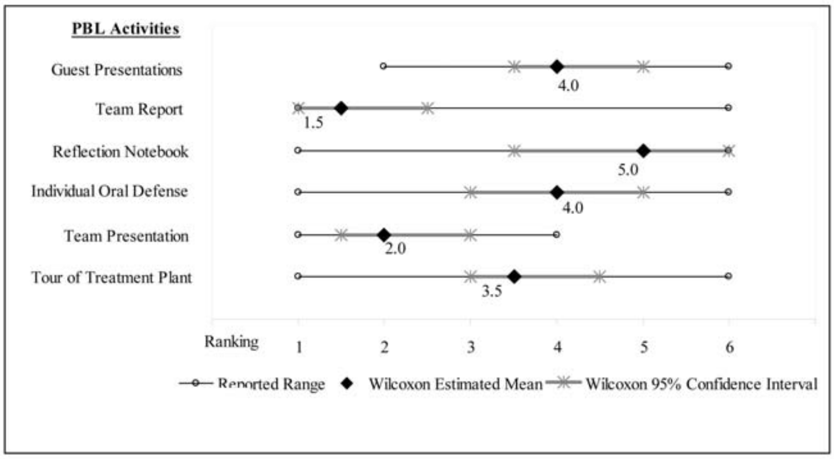

Fig 4. Rank ordering of PBL activities that contributed to student learning: rank scale: 1 = highest, 6 = lowest.

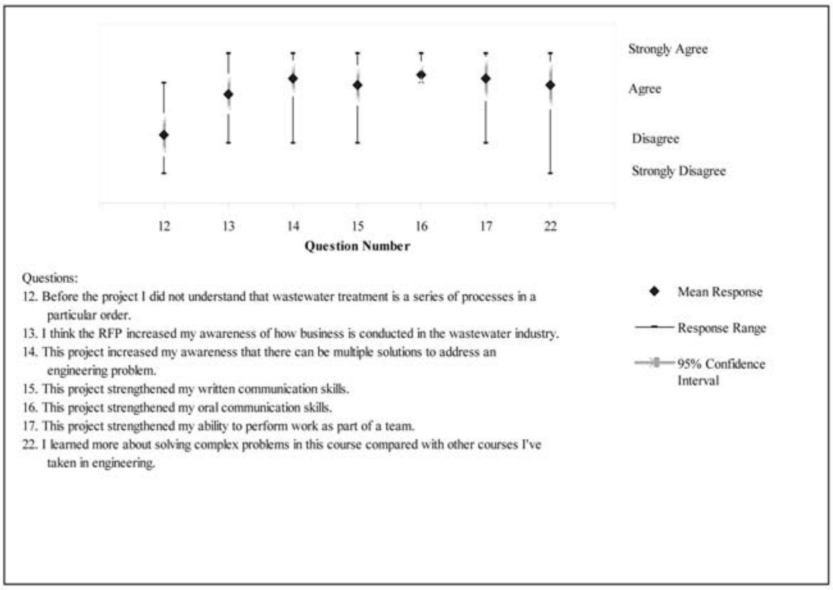

Fig. 5. Students' perceptions of professional competencies within PBL: mean response, response range, and 95% confidence interval.

sorted to determine if graduate students viewed these PBL activities differently from undergraduate students, but the results were consistent regardless of academic rank.

Achieving professional competencies

The secondary objective of the PBL was to integrate opportunities for students to practice specific professional competencies. The authors targeted weakness in professional skills of engineering graduates identified in the Todd, *et al.* survey [2]. Specific interest was placed in students' perceptions of the instructions' impact on their awareness of business practice, written and oral communication, and the ability to work in teams. Seven specific questions from the exit survey have been presented graphically (Fig. 5). These questions were designed to evaluate the students' perceptions of the effectiveness of integrating professional skills in the PBL. The authors interpret an effect of PBL as being 'significant' when the neutral position is outside the confidence interval.

On average, the students reported that prior to the PBL they understood that wastewater treatment was a series of processes in a particular order (Questions 12; Fig. 5).

There was a range of reported responses to Question 13 (Figure 5), which evaluated if the students believed that the use of the request for proposal (RFP) increased awareness on how business is conducted. The average of the group results were positive, indicating that the attempt to make the PBL authentic was useful. When the data was sorted based on graduate versus undergraduate, it was interesting to note that the graduate students were unanimous in their belief that the RFP did increase their business acumen. Although the sample size is small, we think this observation could be an important distinction in students' maturation of how they see themselves working in the future.

Question 14 evaluated the students' belief that PBL increased their awareness that engineering problems can have multiple 'correct' solutions. While the responses range from 'Disagree' to 'Strongly Agree' the average response for the class was slightly better than 'Agree' (Fig. 5).

Questions 15–17, relate to the PBL's ability to strengthen their written communication, oral communication, and teamwork skills, respectively, of the students. The results are encouraging. All of the students reported positive results for these questions (Figure 5). Notably, the reported range for the oral communication skills (Question 16) was small and the average was high (between 'agree' and 'strongly agree').

Question 22 indicates that on average the students believed that they learned more about solving complex problems from the PBL course than from other engineering courses to which they have been exposed (Fig. 5). However, this question also had a largest range of responses.

Effectiveness of PBL

A formal question posed during the exit survey (Question 7) required students to state if they prefer a PBL course or a course instructed without PBL. Seven students stated they prefer the PBL format, five reported that they prefer other methods (without specific discussion of the other methods), and the remaining three stated that they have no preference.

The results of Question 7 appear to be consistent with the results of Question 3 (shown on Fig. 6). On average the students believed that the PBL was a 'Highly Effective–Moderately Effective' teaching and learning tool.

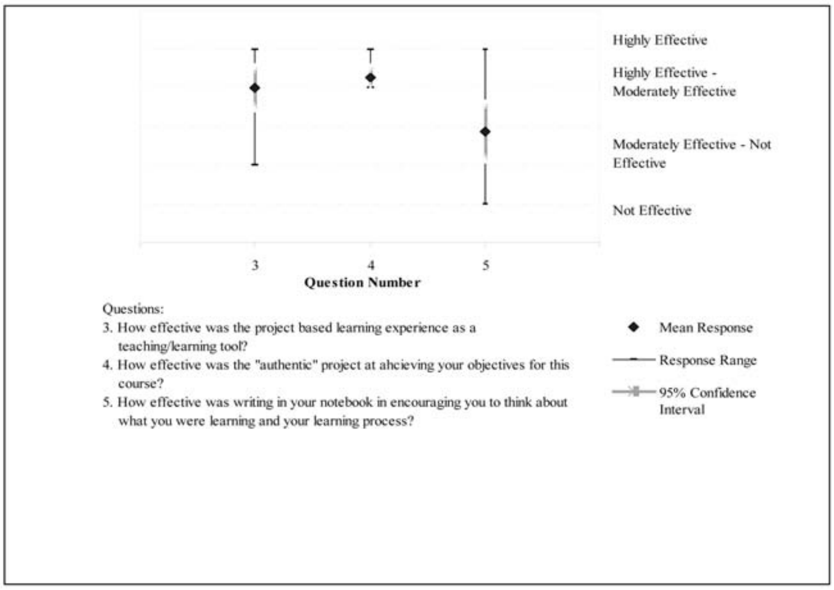

Fig. 6. Effectiveness of PBL, effectiveness of authentic approach, and effectiveness of reflection notebooks: mean response, response range, and 95% confidence interval.

The results of Question 4 indicate that the 'authentic' project was successful in meeting the students' objectives for the course (Fig. 6).

Question 5 has a large variance with this student population. Based on the ranking of learning activities we see that students value the experience relative to other learning activities, yet the defined reflection activities were not as effective for helping students with their metacognition.

Course design and delivery

The survey results for Question 10 (Fig. 7) indicate that the students believe PBL activities require an appropriate amount work for a course. The reported average was consistent among both graduate and undergraduate students.

The students believe that the weekly challenges, designed into the course in accordance with the CBI principles, helped to reinforce the content of the lectures (Question 19).

Questions 18 and 20 were related to the 'driving questions' introduced at the start of each lecture period. The intent of the 'driving questions' was to encourage the students to reflect on their prior knowledge of the subject matter to be presented in that lecture and to subsequently focus the students' attention on the lecture content. Although the average results for Questions 18 and 20 are positive (Fig. 7), they do not provide compelling evidence that the use of the 'driving questions' during this PBL was as useful as the authors might have anticipated.

Question 21, relating to the use of reflection notebooks, was written with a negative tense to avoid students bias. A wide range of results was reported (Fig. 7), which indicates the likely variability in comfort the students had with the reflection process. The reported average was nearly neutral. Unfortunately, due to the negative format of the question, the average indicates that the students slightly align with the belief that the process of writing in the reflection notebooks did not increase their engineering skills. These results are consistent with Question 5 (Fig. 6), which indicates that the students had a large range of reported values relative to the effectiveness of the reflection notebooks in encouraging them to think about their learning. Question 5 also indicates that, on average, the students believe that the effectiveness was slightly on the negative side of neutral.

RESULTS OF PRE- AND POST-ASSESSMENTS

Eight of the fifteen students completed the pre-assessment flow diagram correctly, while a total of eleven students completed the post-assessment correctly. The fact that eight of the students completed the pre-assessment correctly appears to be consistent with Question 12 (Fig. 5) of the exit survey. The results of the exit survey indicate that on average the students believed that they understood wastewater treatment was a series of processes in a particular order, prior to the PBL.

Upon closer inspection of the completed pre- and post-assessments, advanced knowledge of wastewater treatment concepts was noted as illustrated by students who created loops in the system to indicate wastewater recycling (e.g. denitrification with mixed liquor and activated sludge). An indication of advanced knowledge was observed in one pre-assessment and two of the post-assessments.

OBSERVATIONS OF INSTRUCTORS

As an instructor using innovative and non-traditional teaching methods, the desire is to identify clear evidence of student learning. A PBL experience provides inherent opportunities to observe and evaluate student learning. However, often that includes looking for evidence of learning in locations and settings where one typically might not expect to find it.

1. Requests for Information: The previously discussed RFP issued by the 'client' to the 'consulting companies' was assembled to define the problem and the requirements of the PBL. The contents of the RFP included extensive information regarding the existing pharmaceutical wastewater treatment facility. In fact, the RFP intentionally contained more information than the student teams needed to complete the challenges (Weekly and Grand Challenges). The intent was to encourage the teams to thoroughly review the RFP and evaluate what material was needed and what material was superfluous. In addition, critical information, required to complete the challenges, was missing from the RFP. The RFP was consciously designed to be lacking information to encourage the consulting companies to identify what they needed to complete the challenges, determine what was missing, and file a formal request for information (RFI). A minimum level of process knowledge was required on the part of the consulting companies to identify required and missing data within the RFP. Accordingly, the questions and RFIs prepared by the teams provided the instructors with evidence that the students had advanced their wastewater treatment knowledge to the level necessary to ask questions critical to their overall design. In an authentic, industry-influenced approach, all RFIs were addressed through a series of addendums to the RFP. Addendums were formally issued to all teams concurrently.

2. Active Learning: The instructors noted that by comparison to the first half of the semester (water treatment taught with traditional lecture methods), the students were more actively engaged during the wastewater treatment portion (PBL) of the course. Students were hesitant to ask questions and engage in discussion during the traditional lecture periods, whereas the environment during the PBL encouraged and resulted in significant student participation. The number and frequency of questions, as raised by the students, both inside and outside of class, increased during the PBL.

For the duration of the in-class team project time, built into the schedule, the instructors became facilitators and coaches in the learning process. During this time period, the instructors visited with each team to address questions as they arose and to simply observe the activities of the team. All three instructors noted evidence of peer facilitated learning, where concepts were discussed and evaluated as a group, with little or no external guidance.

3. Metacognition: When the notebooks were initially distributed and the students were given their first opportunity to write, there was a clear hesitancy to do so. During the early writing activities, students had to be coached on the process of free-writing. The observations of the instructors indicate that as the project continued, students appeared to be more receptive and in many cases eager to write within their notebooks.

At multiple points during the project, students were prompted to write on a specific topic (e.g. What concepts are you personally struggling with in this class?). Students were then encouraged to share, if comfortable to do so, with their consulting

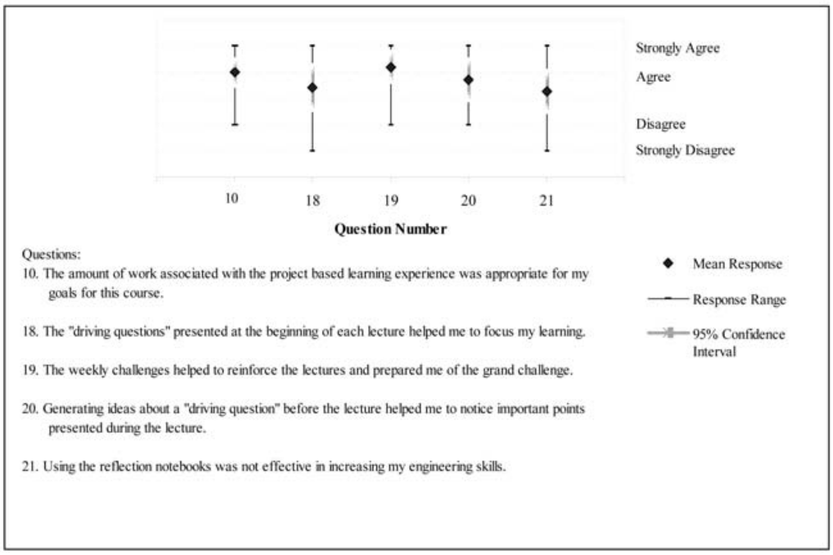

Fig. 7. Student perceptions of the PBL design and delivery: mean response, response range, and 95% confidence interval.

company team members. Then a representative of each company made a brief presentation to the class on a common trait (e.g. common struggle) that was identified within their team. By going through this process students learned that they were not alone in their thoughts and, in fact, many students struggled in the same areas. Further, the course instructors were provided useful feedback and it enabled us to address common concerns shared by class.

The exit survey of student perceptions, related to the use of the reflection notebooks (Question 5 on Fig. 6 and Question 21 on Fig. 7) produced slightly negative results. The authors recognize that using reflection notebooks is not commonly employed in engineering courses. The use of the notebooks may have been better received by the students if they had been referred to as 'design notebooks' in which reflection was encouraged.

One potentially, indirect implication of using the reflection notebooks is the clear increase in perceived knowledge reported by the students in Questions 1 and 2 (Fig. 2). By encouraging the students to think about their wastewater treatment knowledge during the PBL, they may have recognized their knowledge growth indicated on Fig. 2.

A review of the submitted reflection notebooks, after completion of the course, revealed interesting information. In general, the notebooks were used by the students to record prompted reflections. The majority of the students also used the notebooks to record example problems from lectures, project-related calculations, and concepts for addressing the team report and presentation. At least one student embraced the reflection aspect of the notebook and made journal-like entries after each class and each external team meeting.

Perhaps the most intriguing insights into the student mind were found upon inspection of the first formal reflection assigned to the students. After the project roll-out and before students were assembled into their consulting companies, students were asked to free-write on their perception of the project and ideas they had on how to complete the project. The most common themes indicated in the first reflection writing performed by the student's included: excitement, apprehension, and time concerns. The comments about excitement were related to the student interest in the way the project had been designed and presented to them. Several students noted that they were eager to work on an authentic project. One student even noted that he/she was energized by the idea that the pharmaceutical company may implement the ideas presented by the consulting companies. It is worth noting that this student's perception became a reality. The 'client' was ultimately very pleased with the student produced reports and presentations. The instructors understand that the pharmaceutical company is further investigating the implementation of several of the recommendations made by the student consulting companies.

The student's statements regarding apprehension were not related to project performance. Rather, the initial reflection revealed a concern regarding team members. At the time of the initial reflection, students were aware that teams would be assembled, but they had not yet been identified. Common statements observed in the writing were along the lines of, 'I hope I have good team members that all work hard' and 'I wonder what role I will play on this team.'

Finally, the comments made regarding time appear to be related to the perceived size of the project, the number of requirements, and the timeframe before delivery.

One student made an interesting comment that is worth repeating:

> Initially I [am] a little intimidated by the whole project description and giving a professional presentation to a company, such as [pharmaceutical company]. Presenting my research and ideas has always been something I have been apprehensive about. I think by the end of the project I hopefully will be more confident in myself and my team; as well as our design alternatives. I know this process might not be easy for me, but I think it will be beneficial heading into a professional setting.

Clearly, this student recognized a weakness in his/her professional skills. Specifically identified are presentations and teamwork, as well as consideration of design alternatives. It is encouraging to note that the student anticipated that the PBL would not be trivial, but would be beneficial to his/her future professional career.

4. Professional Competency Integrations: The professionalism of the deliverables was notably better during the PBL than the student prepared work during the non-PBL portions of the course. Students appeared to take more pride in their work and their contributions to the team effort. While much of the non-PBL assignments submitted during the first half of the semester were difficult to interpret and were generally disorganized, deliverables submitted during the PBL (second half of the semester) were prepared and presented in a highly professional manner. During the PBL, students also responded positively and quickly to constructive criticism provided by the instructors. It appears that treating the students as professionals, resulted in them conducting themselves with a professional demeanor, particularly in their interactions with each other and with instructors.

In addition to more professional deliverables, there was notably more creativity and originality in the student deliverables during the PBL. The Weekly Challenges were designed to be open-ended. As a result, consulting companies consistently took very different approaches to the same problem. Each company learned to adequately defend their results and recommendations. By comparison, the general student approach to traditional, out of the book problem sets, as used during the non-PBL portion of the course, was to copy information from example problems in the book without a clear understanding of the problems. Regularly, the non-PBL problem sets would produce common mistakes throughout student's homework, illustrating that the students were not successfully applying learned material to a new scenario.

It is interesting to note that among the reports and presentations prepared by the four consulting companies during the PBL, there were three divergent recommendations offered to the perspective client. In each case, the consulting companies provided strong and resourceful support to defend their recommendation. This illustrates that each company developed a unique decision model and weighted various considerations differently. From the student's perspective, this process helped to reinforce that in practice there isn't always a single best solution.

DISCUSSION

Purdue University consistently receives high marks on the quality of its Civil Engineering graduates, yet we still receive criticism from industry surveys and advisory committees that students need to have better professional skills. Specifically, they encourage improvements in graduates' written communication skills and a sense of how professional environments operate. Therefore, the authors refined our learning environment to leverage current theories of how people learn by increasing pedagogical activities that not only focus on the knowledge to be learned, but also on the needs of the learners, assessment methods to help them monitor their progress toward our learning goals and a focus on both a team community and the professional community associated with wastewater treatment. The STAR.Legacy Learning Cycle provides a framework to identify and sequence activities that promote learning, facilitate self guided inquiry and develop a sense of community. The authors have successfully adapted this framework into a civil engineering course.

Additional indications

During the oral defense period, each student was asked, 'based on your experience this semester, what type of problem would you be more comfortable addressing, a water treatment or a wastewater treatment problem?' Of the fifteen students in the course, ten reported a preference for a wastewater treatment problem, two report no preference, and the remaining three report a preference for a water treatment problem.

While the majority of the CE4546 students appear to favor the PBL format and may have developed a deeper understanding and more comfort with the content delivered via the PBL, clearly, the results illustrates that there are a variety of learning styles among students. The use of a PBL experience may serve to replicate industry-type activity but, like all learning tools, it is not a perfect fit for all learning styles.

The results of the survey indicate that the students placed great importance on the team report and team presentation, relative to their personal learning. These two activities correlate to the 'go public' portion of the STAR.Legacy Learning Cycle, which is a critical part of the learning process.

Limitations of the study

There are some inherent limitations of this study that the authors readily identify and offer comments on. Foremost, is the fact that there was no true control group against which to compare the treatment. If the CE456 course was instructed using two separate class sections with fairly consistent characteristics, it would have been interesting to teach one section via traditional lecture techniques and the second section via PBL. While the single class did not permit comparison to a parallel control group, the water treatment portion of the course was intentionally instructed via traditional lecture methods and the wastewater treatment portion of the course via PBL (same group of students throughout).

The majority of the CE456 students had not previously been enrolled in a course that used a problem-based learning approach. Four of the students were enrolled in a project-based senior design course, concurrent to the CE456 course. Accordingly, the novelty of the experience may have produced a slight Hawthorne effect among the students.

Considerations for future use

The following is a summary of alterations that are planned for consideration during the next application of a PBL experience in the CE456 course, or similar courses.

For each of the instructors, this was their first opportunity to design and implement a PBL experience. Accordingly, the decision was made to implement the PBL during half of the semester, rather, than attempt a full semester PBL course. While the results indicate that the CE456 PBL was successful, the schedule for completion was aggressive. The lead instructor is enthusiastic about the results and would like to make the entire course based on the PBL and CBI approach to instruction in the future. Expanding the PBL to a full semester would allow for integrating additional objectives and skill assessment activities.

The rank ordering of PBL activities performed by the students indicates that the report and presentations contributed significantly to their learning. In a full-semester PBL a set of mid-project deliverables, including a report and presentation, would allow the instructor(s) to provide useful feedback that can be incorporated into the final document.

The 'consulting company' teams were assembled by the instructors with the purpose of creating evenly balanced teams with respect to gender, international status representation, and undergraduate/graduate status. While the majority of the teams appear to have functioned well, they were assembled without regards to personality type. More effective and efficient teams might be assembled if personality types of students and other variables were considered in the process of creating teams.

Even though the teams observed during this study were successful in meeting the required deadlines for deliverable, they were not immune to the common human nature of leaving activities uncompleted until the deadline looms near. Incorporation of project management type responsibilities into the PBL might prove beneficial. Teams should be required to identify and plot (Gantt chart) their primary and secondary milestones and corresponding dates. A team's ability to meet their self-imposed deadlines should be assessed as a graded activity.

CONCLUSIONS

This study indicates that the 'problem to project' approach to instruction develops students' expectations of what it means to be a professional and the skills associated with that as well as advancing their knowledge of wastewater treatment. This study focused mainly on students' self reports to indicate the potential of this approach. However, the informal review of students' work products (e.g. weekly assignments) indicate that learners improve their professional skills in the PBL part of the course compared with what they produced during the traditional part of the course. In addition, the PBL permitted integration of professional competencies required by ABET EC 2000 and requested by industry. This initial study had limits in time to collect and analyze all the students' products, but the authors are optimistic that the student assignments can provide additional research data on the benefits of our instructional approach.

The implications for student learning are positive. However, the initial design and implementation of a PBL experience can be a time consuming activity. The instructors of the CE456 course selected specific aspects of problem-based learning and challenge-based instruction for implementation. Complete implementation of all PBL and CBI principles, in addition to professional competency integration, would have been difficult. Educators wishing to perform similar activities within their courses should be selective of the PBL and CBI activities appropriate for their class size, learning objectives, and course content.

Replication of this study with a larger student population and, if enrolment permits, performance of a PBL in parallel with traditional lecture techniques, is encouraged.

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