

Implementing a Problem-Based Multi-Disciplinary Civil Engineering Design Capstone: Evolution, Assessment and Lessons Learned with Industry Partners

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Abstract - In response to the ABET2000 criteria and the industry feedback concerning program needs and outcomes, many Civil Engineering Programs have made fundamental changes in their curriculum. Most notable are the attempts to create capstone design experiences that provide rewarding experiences for seniors as they participate as members of multidisciplinary teams. This manuscript details the evolution of a civil engineering design capstone experience at a research extensive university that attempts to meet ABET requirements, discusses measures to assess communication competence, and presents lessons learned while working with industry partners.

We begin with a review of the curricular enhancements and related responses by the industry that have occurred over the past six years since ABET2000. Furthermore, we provide a pragmatic discussion of “lessons learned” in order to respond to a call from attendees of the 2006 national ASEE conference for details about integrating Team-based Learning (TBL) and Problem-based Learning (PBL) into the capstone. Finally, we provide a candid discussion of lessons learned about industry involvement, the use of actual clients, student and instructor workload management and realistic project management.

Keywords: Team Based Learning, Capstone Design, Assessment

INTRODUCTION

For the past decade, engineering educators have made considerable progress in articulating expected core competencies (e.g., discipline-specific knowledge, communication skills, problem-solving skills, etc.), publishing detailed program outcome assessment matrixes [Felder & Brent, 5; Koehn, 12; Olds & Miller, 28], and proposing strategies to promote skill development [Woods, et. al., 33] consistent with ABET2000 criteria. Curricular enhancements are also occurring that integrate design content into meaningful capstone experiences [Felder & Brent, 5; Grigg, et. al., 8; Little and Cardenas, 16] that may also include community-based projects [Padmanabhan & Katti, 29]. The purpose of the current manuscript is to discuss the evolution, assessment, and lessons learned with the implementation of a problem-based multi-disciplinary engineering design capstone. We begin with a review of the curricular enhancements and related responses by the industry that have occurred over the past six years since ABET2000. Next, we provide a pragmatic discussion of “lessons learned” in order to respond to a call from attendees of the 2006 national ASEE conference for details about integrating Team-based Learning (TBL) and Problem-based Learning (PBL) into the capstone. Finally, we provide a candid discussion of lessons learned about industry involvement, the use of actual clients, student and instructor workload management and realistic project management.

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EVOLUTION OF THE CAPSTONE COURSE

The course became the common capstone design course for all civil engineering students in fall 2004 to replace four different capstone design courses by area (construction, structures, transportation, and water resources). Integration of all students into a single capstone design class was motivated in part by the new ABET rules and initiated to provide a unified effort in developing: teamwork skills, multidisciplinary interaction, communication skills, fundamentals of engineering design processes, and application of engineering design principles to a real engineering project. In addition, this civil engineering capstone design class provides greater breadth in developing cost estimating skills, procurement of work, bidding versus quality based selection processes including a presentation of qualifications based on the project request for proposals (RFP), and how the design professionals, the client and the construction professions interact to construct a project. The current stated objectives of the class are listed in Table 1.

With the capstone design class focusing on the design process, the administration of the class centers on a single comprehensive design project. Prior to the spring semester of 2005 the lead faculty member, in an attempt to relate the course to local engineering events, constructed the project. These events could either be proposed ideas or current problematic situations in need of attention. With the focus on local engineering issues, the instructors decided to team with local consulting engineering firms to give students access to real engineering projects. These projects have real clients, real engineering issues, and real impacts on the local communities. Projects used in the past include the Bluegrass airport expansion (Spring, 2006), Richmond water treatment plant expansion (Fall, 2006), and renovating Kentucky River Lock and Dam 10 (Fall, 2005).

Having outside engineering firms involved with the class has been a real benefit to the student. Especially in the cases when the actual original client also volunteered to participate as the client for the student teams. In each of these cases, the student teams started with the actual RFP from the client (provided by the consulting engineer) and responded to the RFP with a statement of qualifications (SOQ). This was their first formal report. They “interviewed” before the actual client and consultant engineer. The client and the consultant chose the best “company” with who they would negotiate a contract and fee for design services. Of course every company was hired to perform the design service. The students proceeded with conceptual design (Phase 2 report), environmental impact assessment (Phase 3 report), cost estimating and scheduling (Phase 4 report), then ended the semester with the detailed design and specifications (Final report). The student teams present their detailed design to the client and consulting engineers at the end of the semester. While somewhat hectic for the students, the process and the participation from the engineers/clients has given the students a reasonable “real world” experience.

Next, we provide a pragmatic discussion of “lessons learned” in order to respond to a call from attendees of the 2006 national ASEE conference for details about integrating Team-based Learning and Problem-based Learning into the capstone.

ENGINEERING DESIGN CAPSTONE PEDAGOGICAL INNOVATIONS

Team-based Learning [Michaelsen, Knight, & Fink, 25] is a comprehensive pedagogy that is especially relevant to an engineering design capstone because it includes a variety of specific components and relies heavily on a series of student-centered content-intensive in-class activities. This approach was pioneered and developed by Larry Michaelsen, who has written extensively about the approach over the last 25 years (for representative articles see: [Michaelsen, 17; Michaelsen & Black, 20; Michaelsen, et al., 25; Michaelsen, et al., 27]).

The emphasis on team-based learning has parallels in cooperative and collaborative learning models, and the emphasis on the application of the course material has parallels in models of active learning and PBL which are especially conducive to the senior design capstone. TBL was originally designed to cope with the problems of large classes, over 120 students in an academic setting [Michaelsen, et al., 26] and primarily emphasizes learning to *use* concepts rather than merely learning *about* them. Michaelsen [18] states: “becoming a team is a process, not an event. Unless instructors facilitate the transformation of groups into teams, their success in using small groups is likely to be limited at best” (p. 2). This advice is especially important to the implementation and assessment of teaming skills for engineers [Katzenbach and Smith, 10; LaFasto and Larson, 13].

Table 1. The objectives and learning outcomes of the capstone course are:

<p>1) Develop an understanding of the classical Client/Engineer/Contractor project structure typically encountered in practice.</p> <p>a. For a specified project, prepare a detailed analysis of the client, engineer's and contractor's roles.</p> <p>2) Develop the knowledge and ability to perform the programming and planning phases of a project.</p> <p>a. Perform a situation analysis to identify client needs.</p> <p>b. Prepare a technical response to the client's needs.</p> <p>3) Develop the ability to design a system, component, or process to meet desired needs.</p> <p>a. Conduct an engineering analysis and prepare a design to satisfy client needs.</p> <p>4) Develop an ability to function on multi-disciplinary teams.</p> <p>a. Plan and execute all assignments on a team basis.</p> <p>b. Use management and supervisory skills to lead the work on a portion of the term assignment.</p> <p>5) Develop the ability to identify, formulate, and solve engineering problems.</p> <p>a. Describe situations; identify and prioritize problems; identify and evaluate potential problem solutions; select effective problem solutions; identify and evaluate potential adverse consequences for problem solutions; and prepare implementation plans.</p> <p>6) Develop the ability to communicate effectively.</p> <p>a. Prepare and submit technical reports.</p> <p>b. Prepare and make formal, oral presentations.</p> <p>c. Present material in figures, drawings, graphs, etc.</p> <p>7) Provide the broad education necessary to understand the impact of engineering solutions in a global and societal context.</p> <p>a. Identify, analyze, and address the environmental, legal, political, and social factors influencing the selection of problem solutions.</p> <p>8) A knowledge of contemporary issues.</p> <p>a. Cover contemporary issues such as the deteriorating civil infrastructure, sustainability and quality-based selection of professional services.</p> <p>9) Develop the ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.</p> <p>a. Use appropriate computerized project planning, management, and design tools.</p> <p>b. Develop an awareness of techniques used in civil engineering practice.</p>

Major components of the *learning teams* pedagogy include:

- Reading and lectures makes up approximately 25% of the course work; application of the material is 75%(various forms of active and experiential learning).
- Teams of 4-6 students each are formed early in the course and maintained throughout.
- A substantial portion of the course and the grade (35-45%) is based on team performance.
- The team assignments are designed so that no one student could complete the assignment easily; the goal is to engage the entire team.
- Students take periodic "readiness assessment tests," covering the readings and class material, to ensure they are prepared for the application portions of the course. Students take these individually first, then

immediately take them again as a team (while the instructor grades the bubble sheets on the spot for immediate feedback).

- The reward structure and class atmosphere are designed to facilitate cooperation *within* teams but competition *between* teams.
- Within specific parameters, each team designs its own criteria for periodic internal evaluations. The resulting quantitative feedback shared among team members provides a forum for conversations to acknowledge good performance and question poor performance.
- A portion of the team component of the grade (usually 10%) is awarded for helping behavior – as determined by the team members in conjunction with the professor's evaluation.
- This structure results in each team taking responsibility for motivating and monitoring their members from within.

Michaelsen and Black [20] argue that instructional strategies which incorporate team-based learning require a paradigm shift where the traditional model (in which roles include (a) teacher as dispenser of knowledge and (b) students as passive receivers of information; and subject mastery is determined by testing individual students) is replaced by a team learning model (in which roles include (a) instructor as course designer and manager of overall instructional process and (b) students as active participants who are accountable and responsible for their learning).

The four primary features of TBL that are critical to the engineering design capstone are: (a) permanent and purposefully heterogeneous work groups; (b) grading based on a combination of individual performance, group performance, and peer evaluation; (c) the majority of the class time devoted to the design project; and (d) a repetitive six-step instructional activity sequence (IAS) which assists students in developing higher level cognitive skills. It is important to note that the two distinctive features of instructional strategies incorporating TBL in the senior design capstone are: (a) a redefinition of the primary roles and responsibilities in the learning process and (b) the formation of an operational learning environment which incorporates use of four new and essential operational tools (course design, classroom management, student group composition, and performance evaluation).

NECESSARY COMPONENTS OF EFFECTIVE TBL LEARNING TEAMS

There are five necessary and sufficient components that must be integrated into team-based learning instructional strategies for engineers. Omission of any of the components limits the ability of engineering teams to be successful in the senior design capstone.

- 1) Heterogeneous composition of diverse interdependent work teams (comprised of between 5-7 individuals) that minimize potential threats from cohesive subgroups.
- 2) Clear, specific, and widely shared group goals that encourage group cohesion.
- 3) Sufficiently difficult and meaningful group activities that do not allow one member of the group to accomplish the task alone.
- 4) Regular, descriptive, specific, relevant, timely, and usable internal peer feedback.
- 5) External comparisons that are emphasized through immediate and ongoing feedback about organizational performance relative to other teams.

A brief discussion of each of the four essential operational tools that provide the foundation for the formation of an operational TBL environment for engineers (e.g., course design, classroom management, student group composition, and performance evaluation) follows.

Course Design

Michaelsen and Black [20] argue that successful instruction using TBL is dependent on course design in which “instructors must focus on creating two very different types of instructional activities. One type must focus on

building a sound student understanding of basic concepts. The other is to design activities that focus on building students' higher level thinking and problem solving skills" (p. 3). Designing activities for the classroom is perhaps the most difficult obstacle to successful use of learning teams. The single comprehensive design project divided into multiple phases provides an excellent activity for TBL. The four questions that must be answered in order to implement TBL in the engineering design capstone include: 1) What do I want the students to be able to *do* when they have completed this unit of instruction (desired educational outcomes related to communication)?; What will the students have to *know* to be able to do it (course content)?; How can I tell what students have *already learned* on their own or from each other so I can build from there (readiness assurance/assessment/feedback)?; How can I tell whether or not students can effectively *use* their knowledge (application of course concepts)?

Classroom Management

When using the TBL model, the majority of instructor effort occurs before the course begins. Preparation and organization are keys to successful incorporation of the TBL model in the engineering design capstone. While the primary classroom management tool in the traditional learning model is lecture, classroom management in the TBL model is accomplished through a six-step Instructional Activity Sequence (IAS) [Michaelsen, Fink, & Watson, 22; Michaelsen, et al., 25]. The IAS is repeated for each major unit of instruction (typically three to five times).

Michaelsen and Black [20] argue "the most unique feature of the IAS is that there are no formal presentations by the instructor until students have studied the material and completed the individual and group readiness assessment tests" (p. 5). The Instructional Activity Sequence includes working through the following six-steps: 1) Individual Study; 2) Individual Testing (Readiness Assurance Test—IRAT); 3) Group (Team) Testing (Readiness Assurance Test—TRAT); 4) Written Group Appeals; 5) Instructor Feedback; and 6) Application-Oriented Activities.

Step one (individual study) ensures that engineering students prepare for class by studying assigned instructional materials. Steps two through five constitute the Readiness Assurance Process (RAP) [Michaelsen et al., 27, Michaelsen, Fink, & Watson, 22]. Step two (individual testing) provides a diagnostic tool for determining student readiness and promotes individual accountability. The individual test consists of 15-20 multiple choice and short answer questions taken from assigned readings and/or homework type problems. To provide immediate feedback to both instructor and students for a unit of instruction, both team and individual tests are scored in class. Step three (group testing) ensures group accountability and peer teaching. The group/team test is identical to the individual test and is taken after the completion of the individual exams. Immediate scoring provides instructor and students with feedback. Yost, Lane, and Blandford [34] recently demonstrated that engineering teams can outperform the strongest individual within a team. Step four (written group appeals) increases learning and enhances group cohesiveness. Michaelsen and Black [20] believe that written group appeals "galvanize a group's negative energy from having missed questions into a focused review of potentially troublesome concepts" (p. 6). Written appeals may come from groups—no individual written appeals are accepted. If the team appeal is granted, however, individuals in the team writing the appeal should also be given credit. Step five includes providing feedback to students with additional explanation prior to the application of course concepts. Instructor skills such as processing, debriefing, and facilitating discussion, greatly affect the impact on student learning. These skills are similar to those required to lead discussions in a traditional instructional environment, but require more knowledge. Since the TBL model encourages negotiation of the learning environment, it is likely that students will challenge an instructor's knowledge more than in traditional learning situations. Therefore, an instructor must be prepared, knowledgeable, and competent. Step six requires the use of application-oriented activities to help students grow in self-confidence while developing a thorough understanding of the class concepts. This step can be problematic and even detrimental with ineffective group assignments. Michaelsen and Black [20] believe that group assignments simultaneously accomplish four major objectives: *promote learning of essential concepts or skills, build group cohesiveness, ensure individual accountability, and teach students the positive value of groups*. Six characteristics of effective group assignments include: 1) Production of a *tangible output*; 2) Impossible to complete without *comprehension* of course concepts; 3) Sufficiently *difficult* to eliminate completion by an individual member; 4) Majority of *time should be spent engaged* in activities; 5) Applicable to real world issues or problems (*pragmatic/applied*); 6) Interesting and/or *fun*. Again, the single comprehensive design project is especially well-suited for step six.

Michaelsen, Black, and Fink [19] details procedures for preventing group problems and developing effective assignments to be used in designing application-oriented activities. Michaelsen and Black [20] suggest "the application activities, group projects and exams employed should look and feel like the kinds of things you hope students would be able to do individually once they have completed the unit of instruction" (p. 6). The application

of course concepts (step six) should constitute approximately 75% of total class time, whereas the readiness assurance process (first five steps) should constitute no more than 25% of class time. The project implemented in the engineering design capstone is especially appropriate for TBL because it includes a variety of specific components and relies heavily on a series of student-centered content-intensive in-class activities.

Student Group Composition

The formation and development of TBL learning teams enable students to move from a passive role in the traditional learning model to a more active role where they are accountable and responsible for their learning. Michaelsen, et al., [23] report that “the development of properly managed, permanent and purposefully heterogeneous learning teams is key to successfully increasing students’ willingness to accept responsibility to ensure that learning occurs” (p. 132).

TBL can only be successful when a substantial part of the course grade is based on group performance and the groups receive regular and immediate feedback on how they are doing in relation to other groups (which causes students to take pride in their groups’ success). Performance evaluation, therefore, is an important component in the TBL model and assists in facilitating assessment of the senior design capstone.

Performance Evaluation

The final key procedure for the implementation of learning teams in the engineering design capstone involves three essential components related to performance evaluation: individual performance, group performance, and peer evaluation [Michaelsen and Schultheiss, 24]. Michaelsen, et al. [21] encourage the involvement of students and teams in the development of fair and equitable grade weights. The philosophy is that students will support a policy that they help to create. Lane and Trader [15] have recently provided details about peer evaluation procedures and criteria implemented by engineering teams in the design capstone.

The primary problem with assessment is the need to document changes over time. Engineering and communication researchers alike are concerned with demonstrating specific improvements in engineering students’ speaking, writing, and teaming. How these improvements are translated is largely a function of existing measurement tools and competing agendas. Assessment is especially important in light of current mandates from the Accreditation Board for Engineering and Technology (ABET) that require engineering programs to assess and demonstrate that their graduates have an ability to function on multidisciplinary teams and an ability to communicate effectively [Felder & Brent, 5; Koehn, 12]. Most engineering professionals agree that communication “performance skills” can be taught and assessed [Shurman, et al., 32] but they struggle to address ABET mandates with incomplete or inaccurate information regarding pedagogy and assessment [Felder & Brent, 5; Ford & Riley, 7; Seat & Lord, 30; Seat, et al., 31; Woods, et al., 33]. Fortunately, engineering scholars have collaborated with communication researchers to design rubrics that can be used to assess teaming, writing, and speaking (TWS) skills [Dannels, 1; Dannels, 4; Dannels, Dannels et al., 2; Darling & Dannels, 3; Kmiec, 11] and to develop effective assessments of team performance skills [Gulke, et al., 9].

CORE COMPETENCIES

Innovative engineering curriculum assessment has been designed around several core competencies including: ***fundamental knowledge*** (e.g., mathematics, physics, chemistry), ***engineering skill*** (e.g., analysis, synthesis, experimental methods), ***discipline-specific knowledge, career success*** (e.g., advancement, life-long learning), ***social awareness*** (contemporary issues, ethical and professional considerations) and ***performance skills***. Dimensions of specific performance skills include ***communication skills*** (e.g., giving and receiving feedback, identification of strengths and shortcomings, speaking skills, content, structure, support, delivery, writing skills, graphical skills, technological skills, translation skills), ***teaming skills*** (e.g., interpersonal, conflict, problem-solving, decision-making, self-management, individual and shared accountability, peer evaluation), and attitudes/commitments to improving communication skills (e.g., relevance, motivation, commitment, etc.). It is imperative that engineering and communication educators, practitioners, and researchers continue their collaborative efforts to develop effective and appropriate strategies and design tools to assess engineering student skill competencies [Ford & Riley, 7; Lane, 14].

ASSESSMENT STRATEGIES

Several rubrics and assessment strategies were implemented as part of the curricular changes to the multi-disciplinary civil engineering design capstone. Engineering administrators and faculty were most concerned with ABET mandates to demonstrate that civil engineering graduates have an ability to function on multidisciplinary teams and an ability to communicate effectively. Assessment instruments were pilot-tested to measure attitudes, team performance skills and oral presentation competencies. Gap analyses were conducted to determine discrepancies between perceptions of the relative importance of specific communication skills and the perceived performance competencies of senior engineering students. Evaluation strategies included self-assessments, within-subjects pretest-posttest comparison experimental designs, external (alumni/industry/employer) product evaluation, and peer evaluation strategies. The two most frequently implemented strategies were the *workshop* model and the *consulting* model. The workshop model required that a communication faculty provide presentation skills training to undergraduate engineering students in one 2-3 hour session or 2-3 one-hour sessions. The consulting model, on the other hand, required that a communication professional schedule limited time outside of the regularly scheduled class to consult with individual groups about how to improve specific communication competencies. Page limitations prevent the elaboration of the specific assessment instruments in the current manuscript but we are committed to working collaboratively to test sensitive assessment instruments (with acceptable psychometric properties) and strategies to adequately assess student engineering communication skill competencies (see [Lane, 14]).

LESSONS LEARNED

Even with the rewards of including real projects, real engineers, and real clients, there are numerous benefits and costs associated with collaboration. It should be obvious that the benefits include a real engineering project, gaining insight into the workings and management of a project, having access to senior and professional engineers, learning how to interact with clients, and seeing how the design process fits together with the various stakeholders. We have been fortunate to have willing participants from industry to fill this role.

In seeking engineering consultants and projects, we outline their potential involvement so that they are aware of their roles. The consultants in the past have agreed to commit to the following: be part of two presentations (the “interview” and the final design presentation), present the RFP and discuss with the students the major issues of the project, present the technical tools needed to complete the design task, be available through email for informal questions and two formal Q&A class sessions, and host a site visit field trip. Of course during the entire process the consultant, and to a lesser extent, the client, give the students feedback. Thus they are fully participating in the educational goals of the class. This by itself is a challenge since the engineers/clients are not educators, so they tend to focus on deficiencies rather than focusing on both strengths and weaknesses. So the instructor takes on the additional role of educating the engineer/client in ways to be an educator. This is a glimpse into potential costs to the instructor or the students. The biggest upfront cost is the effort needed to find a consultant (with an engaging project) who is willing to donate company time—about 20-30 hours over the course of a semester. Until recently this has been relatively easy. Then there are the scheduling issues. The instructor needs to work with the engineers, within the context of the class schedule, to schedule the engineer’s presentations of the project, Q&A session (s), a field trip, and the student presentations. Coordinating multiple schedules requires persistence and patience. Of course the students must set aside time for a field trip and extended time during final presentations.

In consideration of the student’s perspective, the biggest challenge for the faculty and consultant is limiting the scope of the project to be manageable and executable in the context of a 4-credit semester long class. For example when the students performed the Environmental Assessment (EA) for the airport project, they were given approximately 3 weeks. The consulting engineer expressed his concerns about how we expect a team of 5 or 6 students to do the work that took the consultant more than two years to perform. This is where the experience of the consultant was invaluable for giving the students an understanding of the significant issues for the EA specific to the project, providing the students with a reference list of governing federal regulations and agencies, and hence narrowing the student’s scope. The challenge was to narrow the scope so that the students could meet the quality expectations of the faculty, without becoming overwhelmed. Attempting to balance the workload for the students can be an unforgiving process if the students become completely overwhelmed. Having the project divided into phases, with associated deadlines, has helped keep the students diligent and on task. Unfortunately the necessary decomposition does not necessarily coincide with a real world work breakdown structure. The classroom learning

environment and load balancing issues require a serial process of the project, whereas an engineering firm has the ability to perform the design tasks in parallel.

The current manuscript detailed the evolution and curricular enhancements, the performance evaluation and assessment strategies, and lessons learned with the implementation of a problem-based multi-disciplinary engineering design capstone. If the capstone design course is well planned, coupled with a willing consulting engineer and project, the benefits to the students are unmatched in any undergraduate class. Since the students are graduating in the semester in which they enroll in the class, their experiences serve as a bridge between academic work and career work.

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