AC 2009-1766: PROJECT-BASED TEACHING OF ENGINEERING DESIGN

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Abstract

As a result of major revisions to the mechanical engineering design curriculum, the United States Military Academy (USMA) has offered the new course, Mechanical Engineering Design, since 2006. This paper describes the evolution of this course and its associated annual course assessments. In addition, conclusions are provided about the efficacy of those changes. In the initial offering of the course, students were assigned to their senior capstone project teams and the formal design process was taught "just in time" for students to apply the process to their capstone projects. Based on both student and instructor assessments from the initial offering, the course was revised to teach the design process in the context of two simple projects (design a portable illumination device and design a device to store a West Point class ring) followed by the senior capstone project. The illumination device project served as an in-class example throughout formal instruction and the ring storage device project provided context for students' individual out-of-class work (homework, prototype fabrication, and final project report). Upon completion of the ring storage device project, students began their one and one-half term capstone design projects. Course revisions from the initial offering to the second offering have been reported previously in the literature. This paper briefly summarizes those earlier changes and describes revisions incorporated in the latest offering as a result of student and faculty feedback from the second offering. Recent changes include expanding the open-endedness of the in-class project and revising the timing of and expectations for the individual project. In its third offering the course effectively introduced topics in such a manner to encourage individual proficiency of design concepts before proceeding to the team-based capstone projects. Course feedback and subsequent analyses provide insight to the effectiveness of these evolutionary changes to the course, Mechanical Engineering Design. Faculty teaching engineering design in disciplines other than mechanical engineering can apply the underlying strategy to motivate student learning used in Mechanical Engineering Design.

Introduction

Most mechanical engineering curricula include an opportunity to design and build a product as part of a capstone design experience. As reported by Larson and Keat[1], 93% of mechanical engineering programs surveyed include a capstone design course while 91% of programs require students to build a working prototype. The mechanical engineering program at the United States Military Academy is one such program that affords both design and prototyping experiences as part of the capstone project.

Before attempting a capstone design project, students must learn the formal design process to guide their efforts. To introduce the formal design process, mechanical engineering programs typically employ one of two strategies: teaching the design process as a separate course[2-7] or integrating formal design process instruction with the capstone project[8-11]. The USMA mechanical engineering program has employed both strategies as its formal design process instruction has evolved into its current form.

The USMA mechanical engineering program consists of a robust core program of 26 mathematics, science, humanities, and social sciences courses required by all Academy students and 18 mechanical engineering-specific courses. Although design experiences are integrated into required courses in thermal-fluid systems, heat transfer, and engineering materials, formal mechanical design process instruction occurs in the second course of a three-course design sequence: Manufacturing and Machine Component Design, Mechanical Engineering Design, and Mechanical System Design. Given the constrained curriculum, during fall of senior year the formal mechanical engineering design process is taught in Mechanical Engineering Design as a lead-in to a one and one-half semester capstone design project occurring in the second half of Mechanical Engineering Design and continuing into Mechanical System Design.

Mechanical Engineering Design Curriculum

As described previously in the literature[12], the USMA mechanical engineering design curriculum was revised significantly in 2004 and implemented in 2006. Prior to 2006 the design curriculum consisted of three discrete design courses: Introduction to Mechanical Engineering Design that introduced the design process, failure modes, and machine component design; Mechanical Design that presented weapon design; and Capstone Design in which student teams engaged in various design projects. The revised design curriculum introduced significant hands-on manufacturing instruction, allotted additional time for capstone projects, and incorporated a requirement that all capstone projects must include not only design but also prototype fabrication. Mechanical Design (weapons design) was eliminated from the curriculum.

The resulting curriculum deliberately integrated the three-courses in the design sequence. In the first course, Manufacturing and Machine Component Design, students learn failure modes, machine component design, and hands-on manufacturing techniques culminating in the limited design but significant build of a water turbine prototype for course competition. The second course, Mechanical Engineering Design, formally introduces the design process with an individual design and build project requirement and then transitions into team-based capstone projects. In the final course, Mechanical System Design, students complete their capstone projects.

Evolution of Design Process Instruction (First and Second Offerings of Mechanical Engineering Design)

Since its first offering in 2006, Mechanical Engineering Design has been taught three times. Student feedback and the annual course assessment process identify potential areas for improvement in the course. Boettner et al.[12] describe the changes made from the first to the second offering of the course and the resulting improvement in student feedback. A description of the course in its initial format and the changes made for the second offering are summarized below.

In the initial offering in 2006, sixty-four students were enrolled in the course. Students were assigned to their capstone project teams within the first two weeks of the course, and instructors taught the formal design process just-in-time for students to apply concepts to their team projects. Instructors introduced concepts using Power Point slides with limited practical application and in-class hands-on exercises. For homework assignments students were expected to apply the concepts introduced in class to their capstone projects. Due to the diverse nature of the projects, timing and content of assignments did not always align well with every project. Course graded requirements consisted of 72.5% team effort and 27.5% individual effort.

Instructors introduced significant changes to the course in its second offering. Formation of capstone teams was delayed until completion of formal design process instruction that addressed conceptual design, embodiment design, and detail design. Formal design process instruction included a mix of Power Point presentations, traditional chalkboards, and small group exercises with introduction of an in-class thread of continuity (design a portable illumination device) to illustrate each concept and design tool. All homework focused on applying the concepts and design tools learned in class to an individual design project (design a device to store a West Point ring) to reinforce individual learning. Each student was required to build his or her device and submit an individual report for the project by the end of the semester. Instructors provided a standard American Society of Mechanical Engineers (ASME) conference paper template for the individual project final report. Upon mid-semester completion of formal instruction of the design process and design tools, students formed teams and began work on their capstone projects. Both individual (final individual project report and prototype) and team (team charter and two interim team project reports) submissions were required during the second half of the course. In the second offering of the course, fifty-six students were enrolled. Course graded requirements consisted of 32% team effort and 68% individual effort.

Current Status of Design Process Instruction (Third Offering of Mechanical Engineering Design)

The evolution of the Mechanical Engineering Design course continued in 2008 as several changes were incorporated based on ongoing student feedback and faculty assessment (see Figure 1). These changes were focused mainly on adjustments to course structure as opposed to content. In this third offering of the course, sixty-two students were enrolled and course graded requirements consisted of 30% team effort and 70% individual effort.

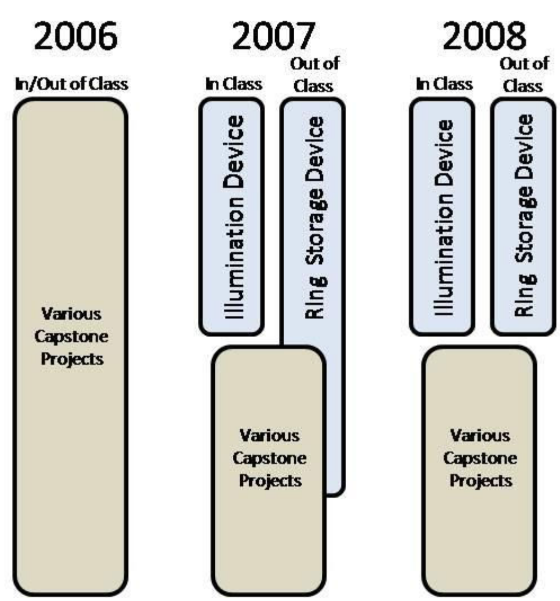

Figure 1. Evolution of the course, Mechanical Engineering Design, 2006 to 2008

In-class exercises continued to utilize a common theme (design of a portable illumination device) to provide context for new course material and design tools; however, a more open-ended approach was used to stimulate student creativity and emphasize the importance of function over form in the early stages of conceptual design. Delaying the selection of a flashlight as the illumination device helped illustrate a more comprehensive application of the design process – better preparing students for their out-of-class and capstone design efforts.

The individual design project (design a device to store a West Point class ring) continued as the framework for out-of-class homework assignments, but it underwent several changes aimed at streamlining the course's transition to group capstone design work. Submission deadlines for the individual design project's prototype and final report were significantly accelerated from the end of the semester to mid-semester. This provided students with a more focused and complete design experience prior to beginning their group capstone design work. Students no longer had to split their attention between two competing requirements at the end of the semester and could apply their previous individual design experience to better anticipate potential difficulties and scheduling conflicts in their capstone projects.

Implementation of the accelerated individual design project timeline was facilitated by two key factors. First, the organization of each interim homework requirement in the format of the final report ensured students followed a systematic and efficient approach in completing a major assignment. Students readily recognized the benefits of methodically completing their final design report as a series of smaller, more-manageable tasks. Figure 2 shows a comparison of student time survey data from 2007 and 2008 – indicating a significant reduction in the severity of the time spike associated with the individual project final report. Instructor feedback also was required to be incorporated into each subsequent homework submission – underscoring the importance of the revision process in achieving clear and concise technical writing results. Second, the creation of a dedicated fabrication laboratory provided the necessary facility to support a more concentrated prototype production timeline (See Figure 3). To alleviate congestion in the fabrication facility, the four sections of the course were staggered with two sections completing prototype production while the other two sections attended three formal lessons on engineering economics, ethics, and project management, respectively. The sections would then reverse roles such that each student had approximately one week to complete the fabrication process. Student feedback indicated that while this was sufficient time to build the prototype, it did not allow enough opportunity to complete finishing details. Subsequent iterations of this syllabus will provide an additional design studio lesson to address this concern.

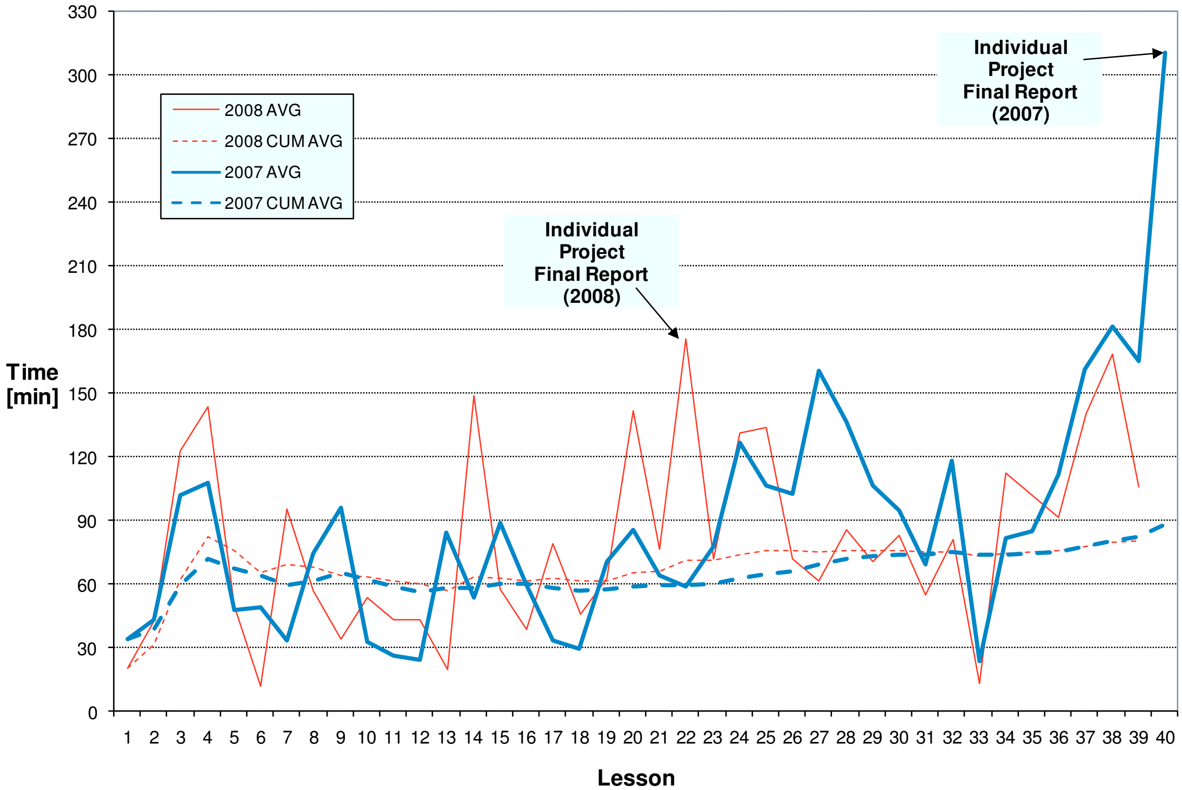

Figure 2. Course Time Survey Data Comparison (2007 and 2008)

Figure 3. Students working on their ring-box in the Fabrication Laboratory

The additional design studio will help address safety concerns that were generated from the shortened individual project timeline. Staggered section schedules and the new fabrication laboratory did not eliminate fully the potential for overcrowding issues during prototype production. Future course offerings will also incorporate more stringent scheduling and maximum occupancy requirements for the laboratory. The standard shop safety briefing will be augmented with a requirement for students to verbally describe their fabrication plan to a laboratory technician prior to using any powered tools. Student inexperience with shop equipment is a systematic shortcoming in West Point's mechanical engineering program. Increased emphasis for hands-on applications will be incorporated into the Manufacturing and Machine Component Design course which precedes Mechanical Engineering Design to provide students with greater exposure and confidence in working with fabrication equipment. Development of a series of short videos summarizing the best practices for specific tools will also serve as a resource for student self-learning and increased shop safety.

In terms of course content, the only significant change in 2008 was the introduction of a guest speaker from industry in place of a formal lesson on materials, processes, and design for manufacture. The guest speaker's presentation offered an important perspective on current industry practices that is difficult to capture in traditional classroom instruction. Students were provided notes covering the formal lesson topics as a self-learning requirement; however, examination results clearly indicated that only half of the students effectively performed this task. Future guest speakers will be asked to include more explicit references to the formal lesson material in their presentation – helping students better recognize each key learning objective.

To enliven and better synthesize course material, short video clips were used to demonstrate real-world applications of the design tools and techniques presented in class. Using the context of popular movies or simple, everyday concepts, the videos provided engaging examples that heightened student appreciation for the design process in action. As described by Norberg[13], videos in the classroom serve as "commercial breaks" which can be effective tools in maximizing classroom attentiveness and building student-teacher rapport. Subsequent course offerings will expand the use of videos to include the presentation of specific manufacturing processes – an area where traditional textbook definitions are particularly insufficient.

Year to Year Course Assessment Results

Anonymous online student course feedback for the last three offerings of the Mechanical Engineering Design course is presented here. Results from student feedback indicate that the third offering of the course rated significantly better than the first offering and slightly better than the second offering of the course. Figures 4 and 5 represent the results of the university-wide and course-specific questions respectively. The assessments were rated on the Likert scale with a range of 1 (strongly disagree) to 5 (strongly agree).

Seven of nine university-level questions rated higher in the most current course offering in comparison to the second offering. Most notable were improvements in Question A4 (My instructor demonstrated respect for cadets as individual), Question A6 (My motivation to learn and to continue learning has increased because of this course), and Question B2 (In this course, my critical thinking ability increased). Notable decrease in rating was seen in Question B3 (The homework assignments, papers, and projects in this course could be completed within the time guideline).

In a similar manner, seven of nine course level questions rated higher. Notable were improvements in Questions E6 and E7 that address design communication and management.

The course feedback included questions requiring responses. Most common favorable comments were about the ring box design project. For example, for the question, "what aspect of the course did you particularly like?" 32 of 62 respondents indicated that they enjoyed the ring box design project. One student, who provided a typical response, wrote, "I enjoyed the fact that we initially designed and built the ring box and then transitioned into our group capstones. This way we understood exactly what the design process was as we began the harder process of designing our capstone." In comparison, to the question, "what aspect of the course did you particularly dislike?" only 10 of 62 respondents indicated the ring box project.

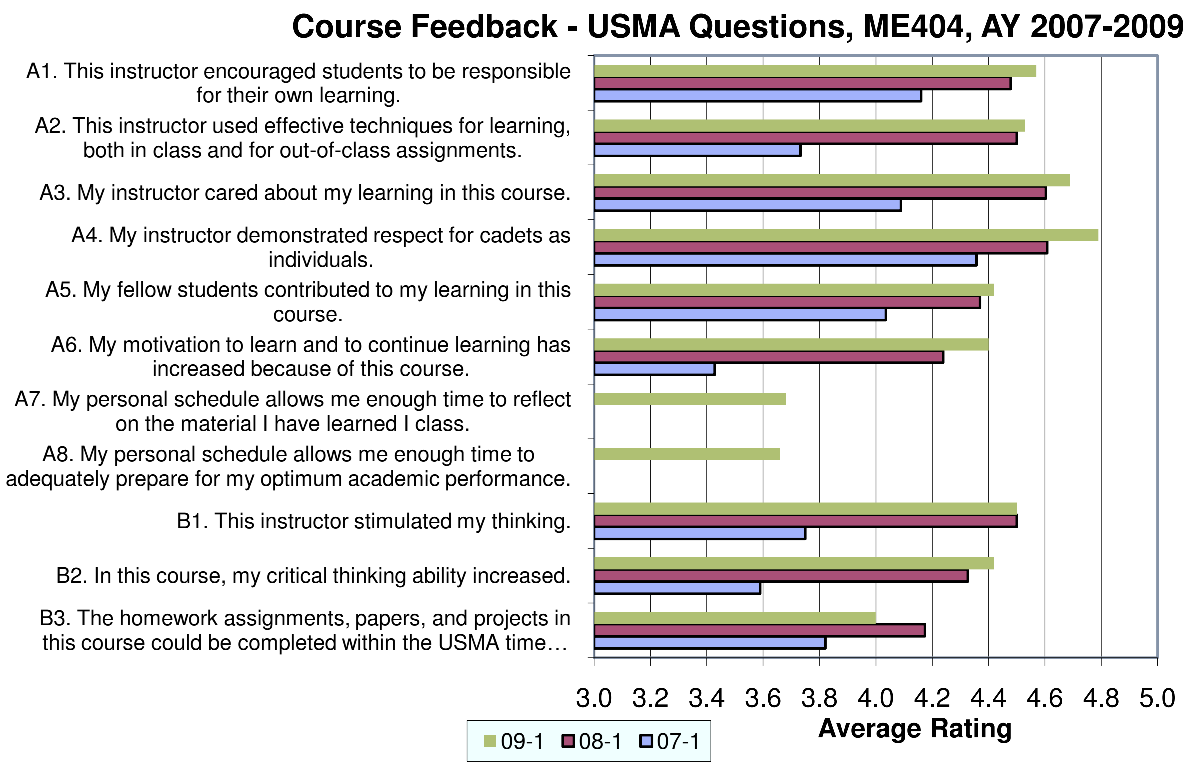

Figure 4. Comparison of Course Feedback (Three Academic Years) – University-level Questions

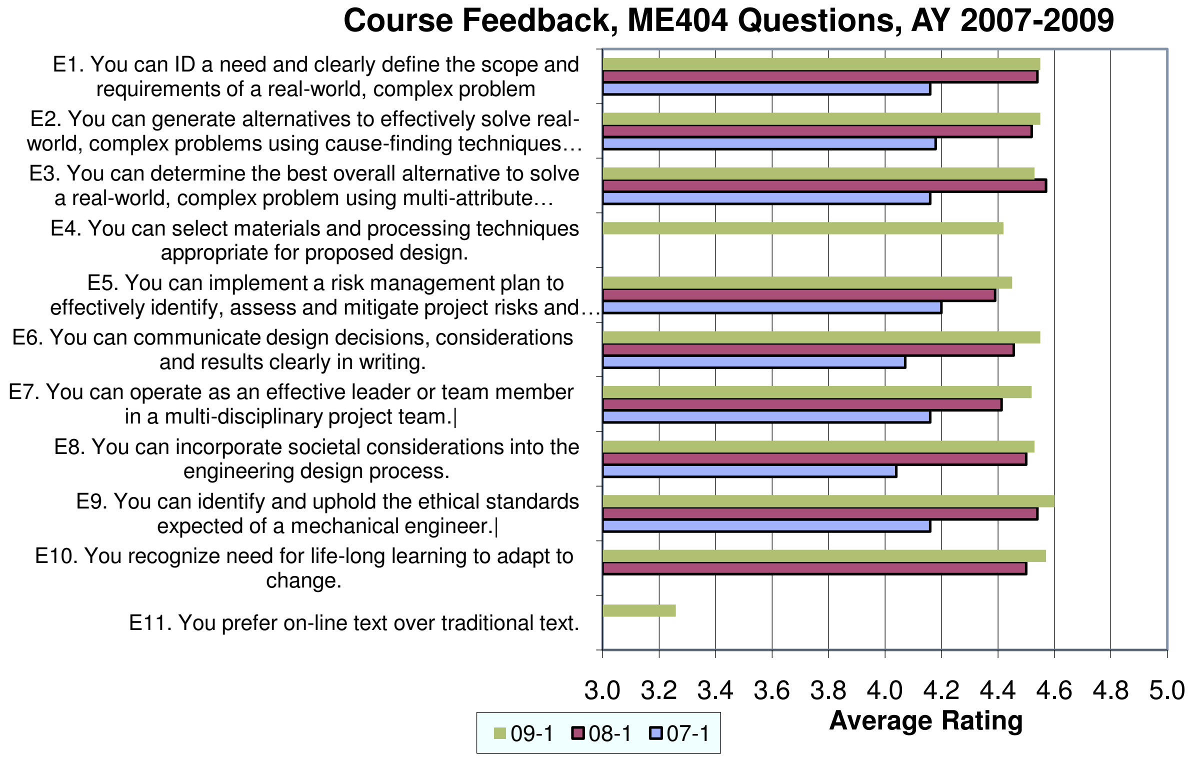

Figure 5. Comparison of Course Feedback (Three Academic Years) – Program-level Questions

Embedded indicators, which are questions embedded in examinations and other graded requirements, provides student performance data year to year. The questions measure the students' performance in terms of the course objectives. Several of these data points are list in Table 1. A comparison of the average percent correct on exam questions for 2007 and 2008 show that student performance in the areas listed was satisfactory in all areas except for material selection. This decrease in performance may be attributed to the addition of the guest lecturer during this lesson.

Table 1. Embedded Indicators (Average % Correct on 2007 and 2008 Exam Questions)

Topic	2008	2007
Pairwise Comparison	97.7	97.6
Quality Function Deployment	94.5	95.3
Functional Decompositon	92.8	95.3
Morphological Chart	93.7	93.3
Decision Matrix	93.9	95.6
Engineering Economics I	88.6	92.9
Engineering Economics II	75.3	81.3
Material Selection	58	85.9
Design for Manufacture	97.6	80.3
Failure Modes and Effects Analysis	77	87.7

Application in Other Disciplines

Dym, et al[14, 15], state that "the purpose of engineering education is to graduate engineers who can design." Teaching the design process is therefore a common theme in most fields of engineering education and the use of capstone design courses is a standard method of imparting this design knowledge to engineering students. For this reason, the techniques used in Mechanical Engineering Design also are highly applicable to other engineering disciplines. Two examples of similar programs at West Point and the observations of some of their instructors are described below.

The Civil Engineering program at West Point provides a two-course design experience to their students. The first course, Site Civil Engineering Design, introduces the civil engineering design process in a manner similar to the one described here for the 2008 offering of Mechanical Engineering Design. Students in Site Design are taught the design process in class and then immediately use these concepts to conduct an in-class example. Students are expected to apply the design process again to an out-of-class Engineering Design Project (EDP). This initial portion of the course is very similar to the 2008 offering of Mechanical Engineering Design in that students learn the design process, apply it to an in-class example, and then use it again to complete an out-of-class project. Dr. Joseph Hanus teaches Site Design and explains that: "students must have all three parts in order to fully understand the design process. If you simply teach them the design process, but don't do the in-class example, they do not perform well on the EDP. If you only teach the process and then conduct an in-class example without making them do an out-of-class EDP, they don't learn as much either." This echoes the experiences from the 2006 offering of Mechanical Engineering Design, where students did not receive an in-class example and were expected to immediately apply the design process taught in class to an out-of-class project. Dr. Hanus also states that, "due to the methodical experience students receive in Site Civil Engineering Design, they are better prepared to perform in the second course in the design sequence, which is the culminating capstone design course." In this second course, the students must rapidly and efficiently apply a design process to a large civil engineering project. Having been exposed to the design process in the first course and having exercised the process, they are better able to meet the expectations in the second course. The overall approach is analogous to the "crawl-walk-run" methodology presented by Dillon and Salinas in 2008.[16]

The Electrical Engineering Program at West Point also provides a capstone experience for their students. This capstone is conducted over two semesters with the first course, Electronic System Design I, covering the majority of the design methodology instruction. The electrical engineering design process also is taught in a similar manner to Mechanical Engineering Design in that students receive instruction on the design process, conduct an in-class example, and then complete an out-of-class robotics project known as a 'semester project.' This capstone experience is similar to the 2007 offering of Mechanical Engineering Design in that the students initiate their capstone projects during the first semester course, after the completion of formal instruction of the design process but before completion of the out-of-class exercise. Dr. Lisa Shay, an Electronic System Design I professor, explains that, "the primary benefit of overlapping the semester project and capstone projects in this course is that it allows the students to start background work on their capstone project at the beginning of the semester and it separates graded requirements which eases the burden on both students and instructors." The Electrical

Engineering Program has found this two-course sequence to be highly effective in teaching the engineering design process to their students.

Clearly students in all engineering disciplines must learn how to design to be effective engineers. Additionally, with senior capstone design projects becoming a standard method of teaching engineering design at West Point and at other institutions, it has been “a natural evolution to move to design projects that involve multiple disciplines to broaden the student’s education into those other disciplines.”[17] These multidisciplinary design projects provide great benefit for students as outlined by Shay, et al. in 2004.[17] Ensuring that the students who participate on these multidisciplinary teams have gained a similar appreciation of the design process from their various disciplines would be helpful. For these reasons, the evolution of Mechanical Engineering Design is highly applicable to other engineering disciplines as well.

Conclusions

Like most undergraduate mechanical engineering programs, the program at the USMA provides its students both design and prototyping experiences as part of the culminating capstone project. Although engineering design experiences are integrated into almost all of the engineering courses, a three-course design sequence is included in the curriculum to provide formal instruction in design and manufacture as a lead in to the capstone project.

Presented in this paper is the evolution of the three-course design sequence from 2006 to 2008. The design curriculum was revised significantly in 2004 and implemented in 2006 with increased focus on hands-on application and a requirement that all capstones have a build component. The revised three-course design sequence includes: Manufacturing and Machine Component Design, Mechanical Engineering Design, and Mechanical System Design. Comparison of the 2006, 2007, and 2008 offering of the second course in design, Mechanical Engineering Design, is presented with student course feedback data, time survey, and embedded indicator student performance information.

In the 2006 offering, the formal design process was taught using the individual team capstone projects as the design problem. Based on both student and instructor assessments from the initial offering, the course was revised in 2007 to teach the design process in the context of two simple projects (design a portable illumination device and design a device to store a West Point class ring) followed by the senior capstone project. The illumination device project served as an in-class example throughout formal instruction and the ring storage device project provided context for students’ individual out-of-class work (homework, prototype fabrication, and final project report). Upon completion of the ring storage device project, students began their one and one-half term capstone design projects. Course revisions from the initial offering to the second offering have been reported previously in the literature[12]. In the latest offering, the in-class project was left open-ended to increase the design space and the out-of-class individual project expectations and timeline were changed to enhance transition to students’ capstone projects.

Student feedback data for the three academic years show that the 2007 offering saw drastic improvement in feedback followed by slight improvement in 2008. Time survey data shows that the 2008 changes in out-of-class work proved to be effective in reducing time spike preparing the design report. Time surveys also show that overall time spent out of class per lesson dropped from near 90 minutes/lesson to 80 minutes/lesson. Embedded indicators show that student performance on examinations generally remained steady from 2007 to 2008.

Based on student and faculty feedback, embedded indicators, time survey, and student performance on capstone projects, the authors conclude that the project-based approach with an in-class, out-of-class, and capstone design problems provides an effective teaching and learning framework. The examples from electrical and civil engineering show that this framework is applicable across disciplines.

References

1. Larson, M. and Keat, W.D., 2003, "The State of Mechanical Engineering Design Education: Results of a Web-Based Survey," Proceedings of the 2003 American Society for Engineering Education Annual Conference and Exposition, Nashville, TN, Jun 22-25.
2. Conrad, J., Hoch, D., and Skinner, F., 2007, "Student Deliverables and Instruction for a Senior Design Program Course," Proceedings of the2007 American Society for Engineering Education Annual Conference and Exposition, Honolulu, HI, Jun 24-27.
3. Krouglicof, N., 2003, "The Mechanical Engineering Capstone Design Experience at Union College," Proceedings of the 2003 American Society for Engineering Education Annual Conference and Exposition, Nashville, TN, Jun 22-25.
4. Laguette, S., 2007, "Development of a Capstone Design Program for Undergraduate Mechanical Engineering," Proceedings of the 2007 American Society for Engineering Education Annual Conference and Exposition, Honolulu, HI, Jun 24-27.
5. Dong, J. and Dave, J., 2007, "Design-Build-Test – The Capstone Design Project," Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition, Seattle, WA, Nov 11-15.
6. Choate, R. and Schmaltz, K., 2006, "Improving Student Design Skills through Successive Design and Build Projects," Proceedings of the 2006 ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, Nov 5-10.
7. Azemi, A. and Esparragoze, I., 2006, "Teaching Design Methodology to Undergraduates through Multi-Year Projects," Proceedings of the 2006 ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, Nov 5-10.
8. Ravikumar, P.B., 2001, "Assessing and Improving a Senior Design Project Course for Undergraduates in Mechanical Engineering Based on new ABET Guidelines," Proceedings of the 2001 American Society for Engineering Education Annual Conference and Exposition, Albuquerque, NM, Jun 24-27.
9. Giolma, J.P. and Nickels, K.M., 2002, "Herding Cats: A Case Study of a Capstone Design Course," Proceedings of the 2002 American Society for Engineering Education Annual Conference and Exposition, Montreal, Quebec, Canada, Jun 16-19.
10. Muci-Kuchler, K.H. and Weaver, J.M., 2005, "Using Industry-Like Product Development Projects in Mechanical Engineering Capstone Design Courses," Proceedings of the 2005 American Society for Engineering Education Annual Conference and Exposition, Portland, OR, Jun 12-15.
11. Abu-Mulaweh, H.I., 2004, "Capstone Senior Design: A Small Engineering Program Experience," Proceedings of the 2004 ASME International Mechanical Engineering Congress and Exposition, Anaheim, CA, Nov 13-20.
12. Boettner, D., Byers, L.K., Crawford, B.G., Tamm, G., Rogers, J., Jones, T., and Rounds, M., 2008, "Teaching Design in Context," Proceedings of the 2008 ASME International Mechanical Engineering Congress and Exposition, Boston, MA, Nov 2-6.
13. Norberg, Seth, 2007, "Commercial Breaks in the Classroom," Master Teacher Program 2007 Graduate Paper Anthology, West Point, NY.
14. Dym, C., Agongino, A., Eris, O., Frey, D., and Leifer, L., "Engineering Design Thinking, Teaching, and Learning," Journal of Engineering Education, Vol. 94, No. 1, January 2005, p. 103.

15. Dutson, A.J., Todd, R.H., Magleby, S.P., and Sorensen, C.D., "A Review of Literature on Teaching Design Through Project-Oriented Capstone Courses," Journal of Engineering Education, Vol. 76, No. 1, 1997, p. 19.
16. Dillon, J., and Salinas, J., "Footballs, Rockets, and LEGOs: A Hands-on Approach to Enhancing the Quality of Engineering Design Education," Proceedings of the 2008 American Society for Engineering Education Annual Conference and Exposition, Pittsburgh, PA, Jun 22-25.
17. Shay, L., Hanlon, P., and Goda, B., "Experience with Multidisciplinary Design Projects at the US Military Academy," Proceedings of the 2004 American Society for Engineering Education Annual Conference and Exposition, Salt Lake City, UT, Jun 20-23.