AC 2007-945: THE CONVERGING-DIVERGING APPROACH TO DESIGN IN THE SOPHOMORE ENGINEERING CLINIC

Kevin Dahm, Rowan University

Kevin Dahm is an Associate Professor of Chemical Engineering at Rowan University. He has received the 2002 ASEE PIC-III Award, 2003 Joseph J. Martin Award, 2004 Raymond W. Fahien Award and 2005 Corcoran Award for his contributions to engineering education.

William Riddell, Rowan University

William Riddell is an Assistant Professor in Civil and Environmental Engineering at Rowan University. His research interests include design education, fatigue and fracture mechanics, transportation safety, and enegy efficiency. He is currently sophomore clinic coordinator for the college of engineering.

Roberta Harvey, Rowan University

Roberta Harvey is an Assistant Professor in the Department of Writing Arts at Rowan University. She has been part of the faculty team that teaches Sophomore Clinic I since 1998 and played a key role in the development of the integrated design and communication pedagogy of the course. In addition to engineering communication, her areas of interest and expertise include interdisciplinary learning, collaborative learning and teamwork, meta-cognitive learning, information literacy, and student learning outcomes assessment.

Paris von Lockette, Rowan University

Paris von Locketter is an Associate Professor of Mechanical Engineering at Rowan University. He recieved his Ph.D. from the University of Michigan, Ann Arbor in 1999. His interests include the physics or polymers and numerical / computational methods in materials science.

Eric Constans, Rowan University

Eric Constants is an Associate Professor of Mechanical Engineering at Rowan University. His areas of interest include innovative techniques in engineering education and engineering curriculum reform. His research areas include vibration and optimization techniques. He was the 2005 recipient of the Ralph R. Tector Award from the Society of Automotive Engineers.

Jennifer Courtney, Rowan University

Jennifer Courtney is an Assistant Professor in the Writing Arts department at Rowan University, where she teaches first year writing, College Composition II/Sophomore Clinic, and courses on writing assessment. Her research interests include writing in the disciplines (WID), assessment, and information literacy.

The Converging-Diverging Approach to Design in the Sophomore Engineering Clinic

Abstract

The Sophomore Engineering Clinic at Rowan University is a two-semester sequence intended to teach engineering design and communication. Historically, the course has been taught with semester-long projects, one in the fall and one in the spring. An example from the fall 2003 and 2004 semesters was the Hoistinator project. Student teams of 4-5 were challenged to build a crane that could lift at least 420 pounds, using no more than 75 cubic inches of aluminum and 50 cubic inches of plastic. Teams would receive a score that was directly proportional to the amount of weight lifted, and inversely proportional to the amount of material used. The project was successful in many respects but there was room for improvement in the student's overall approach to the design problem. Students were generally successful at using statics to predict their crane's performance, but the cranes they designed and built were generally not well optimized. Many student teams chose a basic design quickly and after investigating few, if any, alternatives, and in many cases important decisions were made without a quantitative analysis.

During the fall of 2005, the faculty team addressed this shortcoming by 1) establishing a sequence of design projects that increases in complexity, and 2) presenting a converging-diverging approach to design, modeled after a paper by Dym, et. al.[1] Rather than a semester-long project, the faculty provided a four week project on designing bottle rockets followed by a 10-week version of the Hoistinator project. Students were required to document their approach to these problems in detail, showing specific evidence of divergent design and convergent design and specific rationale for the final decisions resulting from these processes. A comparative assessment demonstrated that the new approach had a substantial and lasting impact on student design skills: fall 2005 students not only performed better on the Hoistinator project than earlier cohorts, but also performed significantly better on a spring 2006 Sophomore Engineering Clinic project that was essentially unmodified from previous years. This paper will explain the convergent-divergent design model, provide a description of the design projects, and present in detail the comparative assessments of the effectiveness of this approach compared to prior offerings of Sophomore Engineering Clinic that did not explicitly incorporate the converging-diverging design model.

Introduction

The Sophomore Engineering Clinic is a sequence of two, four semester-hour courses, team taught by the College of Communication and the College of Engineering. Typically, the course has approximately 120 students divided into six sections. The faculty team consists of two or three instructors from the College of Communication and five from the College of Engineering, with each of the four Rowan engineering disciplines (Chemical, Civil and Environmental, Mechanical, Electrical and Computer) represented. Students have two 75-minute lecture sessions and one 160-minute laboratory session each week.

During the lecture sections students receive instruction on technical communication, specifically, technical writing in the fall and public speaking in the spring. Each section has one Communication faculty member for the semester, and for these faculty, each section is viewed as a 3-hour course for workload purposes. In the laboratory portion of the course, three sections meet simultaneously. Consequently, for the engineering faculty, there are two lab sessions each week, each consisting of 60-65 students, and five instructors. For workload purposes this is viewed as a 3-hour course for each member of the engineering faculty.

In the laboratory component of the course, students work on open-ended design projects, closely supervised by engineering faculty. Lecturing is provided as-needed to facilitate the project, but the bulk of the lab time is provided for students to work with their teams. Most of the course deliverables are writing assignments and presentations about these design projects, which are graded jointly by engineering and communication faculty. This course is consistent with growing national trends of integrating design into the early years of the curriculum[2,3,4] and stressing the importance of communication skills[5,6,7].

In both the lecture sections and the laboratory the emphasis on teamwork is exceptionally strong. Design projects are completed in teams of 4-5. Team selection is done by the faculty with the primary criteria being:

- Teams must have compatible schedules so that the students will be able to meet outside of class time to work on the projects.
- Teams have members from a variety of disciplines--ideally, at least one student from each Rowan engineering discipline (Chemical, Civil, Electrical, and Mechanical) on each team.
- Students take the Learning Connections Inventory[8] to evaluate their learning preferences, and teams of students with complementary learning styles are formed.[9]

Historically, each semester had been structured around a single, semester-long design project. This paper describes a new model first implemented in the fall 2005 semester. The following sections describe the Converging-Diverging Design Model and explain how it was used in the fall of 2005 to improve upon previous offerings of the course.

Converging-Diverging Design Model

It is well understood that the open-ended design process is difficult to teach. Evans, et al. for example commented in 1990 that "Even 'design' faculty- those often segregated from 'analysis' faculty by the courses they teach- have trouble articulating this elusive creature called *design.*"[10] A recent paper by Dym, et al.[1] proposed a model for design as divergent-convergent questioning. Convergent thinking is the process of asking and answering questions that reveal verifiable facts. By contrast, when practicing divergent thinking, "the questioner attempts to diverge from facts to the possibilities that can be created from them."[1] An effective design process requires both divergent and convergent thinking, and a workable model is an alternating series of divergent and convergent steps. One begins with a divergent, creative exploration of all the possibilities, followed by a convergent selection of the "best" solution, rooted in sound facts. The facts learned in a convergent step could give rise to new ideas, call into question assumptions made, or

reveal that the "best" solution is still not sufficient to meet the designer's goals. These are all examples of circumstances that would prompt further divergent inquiry.

Dym, et al. go on to observe the convergent inquiry process is one of the great strengths of engineering students, who have experienced years of fact-based homework and test problems with unique "right" answers. Divergent inquiry by contrast "often seems to conflict with the principles and values that are at the core of the predominantly deterministic, engineering science approach."[1] These observations are reflected in the outcome of the fall 2003 and 2004 offerings of the Sophomore Engineering Clinic, which are described in the next section.

The Hoistinator Project

In the fall 2003 and fall 2004 semesters, the semester-long project was a crane design project called the "Hoistinator".[11] This section describes the project itself and discusses outcomes from these first two offerings of the project.

The student teams were provided with a substructure and basic mechanical elements for a crane, and challenged to design a truss that attached to the substructure and was capable of lifting at least 420 pounds to a height of 24 inches. The substructure consisted of a steel base onto which a steel I-beam column was pinned. The column had a number of holes along the edge to be used for pinning structural members. A sliding block along the base provided another attachment point. A motor and gearbox were permanently mounted to the base and a cable take-up reel was connected to the gearbox through a shaft coupling. The weights rested on the steel base and were hoisted by a cable. This structure is shown in Figure 1 and its specifications are given in Table 1. The same substructure was used by all the teams. The teams designed and built the additional structural elements needed to lift the weights, using the materials listed in Table 2. The teams were also required to build a digital timer circuit that would measure the time elapsed between when the weight left the ground and when the weight reached a height of 24 inches.

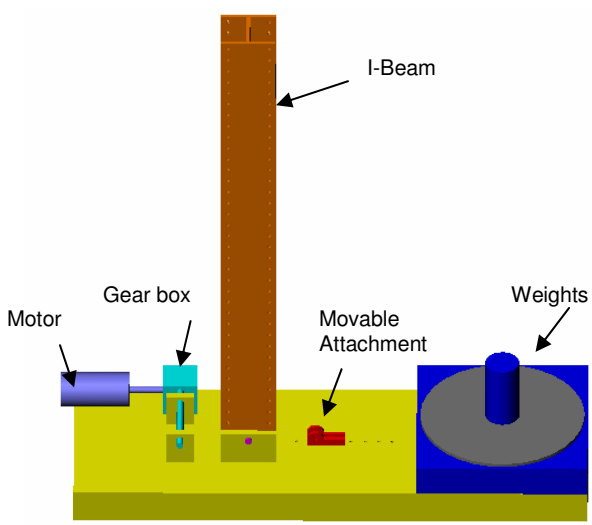

Figure 1: Substructure used by each team to support their crane.

Table 1. Substructure specifications

Motor	3 hp, 1750 rpm
Transmission	30:1 reduction worm gear drive
Column	Structural steel 6" construction-grade I-beam, pinned at base ½" diameter holes drilled in flange on 2" centers
Base	Structural steel C-channel
Timing circuit	Accurately measure lift time from 0 to 24"
Drivetrain	Spool: d = 6", L = 12" UHMW plastic Pulleys: Three each: 2", 3" and 4" ½" shoulder bolts, pulley spacers and shims 3/32" steel cable, 1,000 lb test, 1" minimum bend radius, 16 feet
Weights	Quantity: 20 Weight (each): 70 lbf Measurements: d = 24", t = ½" Position: 33" from column edge to center of weights

Table 2. Structural materials allowed for crane construction

Aluminum	Alloy: 2024-T3 Max volume: 75 in^3 Stock: ½" and ¼" bar stock available in widths between ½ and 1½" in ¼ inch increments, no length greater than 48"
Plastic	Type: TIVAR UHMW (Ultra-high molecular weight) Max volume: 50 in^3 Stock: ½" and ¼" bar stock available in various widths between ½ and 1½", no length greater than 48"
Fasteners	½-13 and ¼-20 SAE Grade 5 hex cap screws with nuts

The students' goal was to build a crane that *lifted a large amount of weight while minimizing use of material*, and to build the most accurate timer possible. These goals were quantified using the "performance equation" given below.

$$Performance = \left[\frac{W}{420}\right] \times \left[1 - \left|\frac{t_m - t}{t}\right|\right] \times \left[\frac{3.5}{LCA_{p-d}}\right] \times \left[\frac{435}{PW}\right]$$

Where

- W is the weight successfully lifted by the crane (lb)
- t is the actual time used to lift the weight (measured using the official timer built by the instructors)
- t_m is the time measured with the student's timer. (A stipulation was made that if the term $\left[1 - \left|\frac{t_m - t}{t}\right|\right]$ was below 0.25 it would be set equal to 0.25, to prevent negative performance values, etc.)
- $LCA_{p\text{-}d}$ is the Life Cycle Assessment Eco-indicator points, calculated by ECO-it software, associated with the production and disposal of materials used in the crane.

- *PW* is the present worth of costs associated with production, use, and disposal of the crane (in dollars).

"Technical merit" of the team project constituted 20% of the course grade and was evaluated solely by the score of a team's crane by this equation.

A detailed description of the technical aspects of the project appears in previous ASEE conference proceedings.[11] Briefly:

- During lab periods, students received instruction on statics, failure analysis, digital circuits, present worth analysis and lifecycle analysis in support of the project. The mechanical and civil engineering students were taking Statics concurrently with Sophomore Clinic, but covering these topics in lab ensured that every student could contribute in any aspect of the project.
- Students were not allowed to test their cranes before a final competition, which was held on the last day of the semester. On the competition day, twenty 70-pound weights were available, for a total of 1400 pounds. Each team attempted three test lifts: the first using 420 pounds, the third using the full 1400, and the second could be any intermediate weight chosen by the team.
- Teams were only required to time their first lift. Note that the equation is structured so that the actual time of the lift (which was beyond the team's control) does not influence the performance equation; all that matters is the accuracy of the team's timer.
- The PW and LCA calculations were based on the amount of aluminum and plastic bar stock used in the crane; peripheral materials like pulleys and fasteners were neglected. Specifications for these calculations were given by the instructors. The net effect of these specifications was that if a team used the maximum allowable quantities of aluminum and plastic, they would have PW~$435 and LCA~3.5, while conserving material leads to lower PW and LCA scores. One cubic inch of aluminum had approximately the same cost, in terms of its effect on the performance equation, as five cubic inches of plastic.
- Each student completed three major writing assignments on this project: two progress reports (one team report, one written individually) due roughly 1/3 and 2/3 of the way through the semester, and a team final report.

After the first two offerings, the faculty team noted the project has many positives: it had an appropriate scope for a semester long project and was recognizable as a practical engineering challenge that included aspects from a variety of disciplines. The students regarded the project as an effective vehicle for meeting the pedagogical goals of the course, as shown by the assessment results given in Table 3, and the element of competition seemed to generate enthusiasm among many of the students. The project was a technical success in that every team (46 teams over the two semesters) was able to fabricate a crane capable of lifting at least 420 pounds, and over 75% of the teams lifted the full 1400 pounds.

Table 3: 2004 Student evaluation of crane project (104 students surveyed)

Question	Mean Response (1=strong disagree, 5=strong agree)
This course assisted me in developing teamwork skills	3.82
This course assisted me in developing multidisciplinary engineering design skills.	3.70
This course assisted me in developing project management skills.	3.93
This course helped me make the link between engineering design and writing.	3.89

The faculty team did have some concerns with the approach of most students to the project, primarily with respect to design of the truss. The intent was that students would brainstorm possible crane designs; use statics and failure analysis to predict how each would score by the performance equation, and choose the best design. Specifications for the writing assignments were crafted to help guide the students in their approach: for example, in the first progress report, students were required to present at least three different crane designs and present an analysis of all three. (By crafting the project this way, the faculty team was substantially attempting to promote a divergent-convergent approach, though Dym's terminology was not used.) However, the progress reports demonstrated that most teams were not taking a sound, quantitative approach. None of the initial progress reports presented an estimate of how any design would score by the performance equation, and in fact fewer than half of the progress reports even mentioned the equation. Many students reported in the second progress report that they had reached a decision concerning a final truss design, but gave only a qualitative rationale for the decision. By the final report, every team had completed a detailed static and failure analysis of the crane they actually built, but very few teams showed evidence that they had analyzed any alternatives. In sum, important design decisions were made without a sound basis, and despite faculty feedback on the progress reports, these decisions were in most cases apparently never revisited.

The above observations reflect Dym's generalization that most of the traditional engineering curriculum emphasizes convergent thinking and thus students are good at it and weak at divergent inquiry. Teams showed little evidence of divergent inquiry, examining few possibilities. While they were good at doing statics and failure analysis calculations (a convergent inquiry arriving at verifiable facts) they in effect treated these as homework problems. Students arrived at an answer and simply reported it, rather than using the results to inform the decision-making process or spawn new ideas. Essentially, most teams reached a decision regarding the design early, and then made it work adequately.

In an attempt to promote better optimization and design skills, during the fall of 2005, the faculty team incorporated the convergent-divergent model of design as an explicit focus of their teaching, passing out copies of the article on the second day of class and referring to it continuously throughout the semester. The next section describes this offering of the course.

Revised Course Structure

The new course structure for fall 2005 incorporated a slightly modified version of the Hoistinator project, but this time it was preceded by a simpler 4-week startup project on building rockets out

of 2-liter soda bottles. Bottles were modified by the addition of wings, etc., partially filled with water, and then pressurized and launched. Schools throughout the country are using various versions of soda bottle rocket projects in science education[12,13] and NASA has proposed standards and lesson plans for grade 5-12 students.[14] Specifications and constraints for this project were as follows:

- The goal was to build a rocket that would fly as far as possible, but distance was measured perpendicular to the plane of the launcher; "sideways" or vertical travel did not count.
- Each team received a 2-L bottle, a can of play doh, a ¼" thick sheet of foam board and a roll of duct tape. No other materials were permitted in construction of the rocket.
- The bottle could be filled with any volume of water up to 2 liters, but no liquid other than water could be used as the propellant.
- For launching, the bottle was pressurized to 60 PSI and launched at a 45 degree angle from the ground.
- Teams had three 160 minute lab periods to modify and test-launch their rocket prior to a final competition.

Students spent the three lab periods experimenting with the effect of parameters such as water volume, size and shape of fins, and mass of play doh added to the nose cone, on flight. They had limited theoretical knowledge (though many tried to make their rockets resemble known aerodynamic objects such as footballs) so it was primarily an exercise in trial and error, consistent with Wood's recommendation[15] for more emphasis on experimentation as a design activity. The trial and error process, however, was made more systematic and quantitative through emphasis on parametric design. To effectively and efficiently converge on the optimal solution, teams focused their design process on systematically varying each parameter while holding the others constant, then evaluating whether changes in that parameter were bringing their rocket's performance closer to their goal.

The project was completed in teams of 4-5 but each student wrote an individual, final report on the project. The model of design as a converging-diverging process was covered explicitly in class. Students were required to use this model as a framework for their final reports, identifying actions taken and decisions made by the team, categorizing them as either "divergent" or "convergent" thinking, and providing a quantitative rationale.

A more detailed description of the bottle rocket project itself was published previously.[16]

The ten week Hoistinator project used the same crane substructure and materials summarized in Tables 1 and 2. To streamline the project to accommodate the shorter time period, the present worth analysis and LCA were eliminated, and this simpler performance equation was used:

$$Performance = \left[\frac{W}{C}\right] \times \left[1 - \left|\frac{t_m - t}{t}\right|\right]$$

By this equation the evaluation of the timer is identical to previous years, and performance is still directly proportional to weight lifted. However, C simply represents the purchased cost of

aluminum ($2 per kilogram) and plastic ($0.80 per kilogram) used in the truss. Costs of use and disposal of the crane are neglected, eliminating the need for lectures on lifecycle analysis and the time value of money. Lectures on statics, failure analysis and circuit design were again presented, this time with emphasis on how each of these activities fit into the convergent-divergent approach to design.

In documenting and reporting their design process, students were again asked to articulate their ongoing progress and eventual results in terms of convergent and divergent design. For example, certain members of each team were tasked with design and fabrication of a switch to turn the timer on and off. One of the two progress report assignments requested a discussion of preliminary ideas considered for the switch mechanism with an emphasis, in this early stage, on innovation over feasibility, which is a hallmark of divergent design thinking. Students were also asked to explain how they developed their optimization strategies—what parameters they identified as important, how they varied the parameters, and how they evaluated the results against their goals—thus reinforcing convergent design thinking.

Results

All of the faculty team's assessment data, summarized in the next three sections, indicate that the new course structure did indeed accomplish the goal of improving design skills by providing a concrete model of effective design practice and instilling the habit of basing decisions on quantitative analysis.

Anecdotal Assessment of Revised Course Structure

The faculty noted the following observations:

- Many of the final reports on the bottle rocket project provided little data and limited quantitative rationale for decisions; this was identical to the primary shortcoming in the 2003 and 2004 Hoistinator projects. However, the 2005 students had the opportunity to re-write these reports, and apply the lessons learned from the experience to the Hoistinator project. This was an important advantage of the two-project structure.
- In the fall of 2004 and 2005, students were encouraged by the faculty, but not required, to do their calculations on Excel spreadsheets, and use the spreadsheet as a tool for examining variations on their designs (e.g., what happens if I change this member from aluminum to plastic, or from ¾ inch to ½ inch?) In the fall of 2004, fewer than 25% of the teams indicated in their reports that they had used this approach, while in the fall of 2005, all teams did.
- In the fall of 2005, in the first progress report, over 90% of the teams presented a statics and failure analysis of three different crane designs. Though the analysis was in some cases incomplete or wrong, students displayed awareness of the need for a quantitative approach.
- In 2003 and 2004, all but one team designed their crane expecting to lift the full 1400 pounds (though some failed.) In 2005, several teams built cranes that they knew would fail at 1400 pounds, because they were attempting to maximize W/C (which was the stated objective) rather than simply trying to make the crane as strong as possible.

- The student assessment of the project was more favorable than in 2004, as shown in Table 4.

Table 4: 2005 student evaluation of crane project (108 students surveyed)

Question	Mean Response (1=strong disagree, 5=strong agree)
This course assisted me in developing teamwork skills	4.32
This course assisted me in developing multidisciplinary engineering design skills.	4.06
This course assisted me in developing project management skills.	4.24
This course helped me make the link between engineering design and writing.	4.02

Comparison of Technical Merit of Designs

An important question is whether the 2005 students' more sound approach led to better final products than previous years. To address this, the scores the 2005 students would have achieved by the 2003/2004 performance equation were computed. The 2005 students earned a mean score of 14.99, compared to a mean of 8.63 by the Fall 2003 and 2004 cohorts. Recall that the 2005 students had only 10 weeks to complete the project, compared to 14 weeks in previous semesters. Thus, the Fall 2005 students' more sound approach to the process of optimization led to significantly improved final products: they outperformed the 2003 and 2004 cohorts even by the 2003/2004 criteria, which was unknown to them.

Impact of Revised Course Structure on Future Courses

Another important question is whether the new structure for Sophomore Engineering Clinic I had a positive impact on the students that lasted beyond the fall of 2005. To assess this, the faculty team used the results of an energy audit project completed in Sophomore Clinic II. This project, which has been described in detail previously[17,18], challenges students to:

- Select a building on the Rowan campus
- Gather information on all the ways in which energy is used in that building
- Make recommendations for methods of saving energy, and
- Give quantitative predictions of the amount of money saved, the energy saved, and the greenhouse gas emissions saved if those recommendations are followed.

This project was run in the spring 2004, 2005 and 2006 semesters, with the same cohorts that previously had the Hoistinator project. It was substantially modified after the first offering in the spring of 2004, but largely unmodified between 2005 and 2006. Thus, the faculty examined the final reports from the spring 2005 and 2006 semesters to determine whether the modifications to Sophomore Engineering Clinic I led to improved performance in Sophomore Engineering Clinic II.

Assessment of the final reports was conducted using rubrics that have been published in *Chemical Engineering Education*.[19] These rubrics were designed to provide an objective assessment of the quality of the work with respect to specific desired learning outcomes, including the ABET A-K learning objectives.[20] For example, one outcome is:

Students will approach tasks involving the acquisition and interpretation of experimental results in a logical and systematic fashion. Specifically, students will make appropriate measurements, record information in a meaningful format, perform necessary analysis, and convey an interpretation of the results to an appropriate audience.

Table 5 below provides four indicators of this ability (listed in the left hand column) and four levels at which a specific sample of student work could be judged with respect to each indicator.

Table 5: Sample rubric for assessment of student reports.

Indicator	Score			
	4	**3**	**2**	**1**
Prepares a technical report with content appropriate to audience	Considers audience fully. Report is exactly geared to correct audience	Considers audience well, but may have a few moments of inappropriate level	Tries to consider audience but may over- or underestimate technical level	Gives little or no regard to the audience
Presents summarized results based on analysis of measurements	Provides clear, complete, correct, and concise analysis. Does not present uninterpreted data	Results are well summarized. Little or no uninterpreted data. Major points are covered. A few minor errors may occur.	Some interpretation and summary is made, but significant data is missing or left uninterpreted.	Students present data incorrectly with little or no interpretation.
Describes in appropriate detail the experimental procedures used	Procedures are clear and succinct.	Procedure is clear, but perhaps a bit short or wordy	Procedure is complete but difficulty to follow. Inappropriate detail level is presented	Procedure is incorrect or incomplete
Uses appropriate methods to estimate and interpret error	Present correct and detailed error analysis and explains its relevance	Presents correct error analysis but does not fully elaborate on its importance	Attempts to address errors but is lacking in procedure or consistency	Makes little or no effort to address experimental error

A significant feature of these rubrics is inter-rater reliability. The scores assigned by different faculty for a given sample of student work have proved to be very consistent[19] without any need to train faculty in use of the rubric.

Table 6 summarizes the desired outcomes and the performance for the spring 2005 and spring 2006 cohorts with respect to each outcome. The scores represent the average values across all indicators for a given outcome. Care was taken to eliminate indicators that did not apply meaningfully to the building energy audit project.

Table 6: Learning outcomes for Sophomore Engineering Clinic II, and mean performance of spring 2005 and spring cohorts with respect to each outcome (4=best, 1=worst)

Desired Outcome	Spring 2005	Spring 2006
Students demonstrate an ability to apply knowledge of mathematics, science, and engineering (ABET - A).	2.48	3.11
Students approach tasks involving the acquisition and interpretation of experimental results in a logical and systematic fashion. Specifically, students make appropriate measurements, record information in a meaningful format, perform necessary analysis, and convey an interpretation of the results to an appropriate audience.	2.19	2.60
Students design and conduct appropriate experiments that effectively use limited resources to obtain the necessary information.	2.00	2.73
Students demonstrate the ability to identify, formulate and solve engineering problems (ABET - E).	2.31	2.90
Students demonstrate understanding of contemporary issues relevant to the field of engineering (ABET - J). Students have an awareness of current technical material (journals, trade publications, web sites, etc.), develop an ability to find relevant current information and use this ability in their curricular assignments.	1.44	2.25
Students have the ability to use techniques, skills, and modern engineering tools necessary for engineering practice (ABET - K). Students apply fundamental principles of engineering to solve engineering problems.	2.17	2.83
Students have the ability to use techniques, skills, and modern engineering tools necessary for engineering practice (ABET - K). Students use the internet and appropriate software packages including spreadsheets, word processors, mathematical packages and process simulators to assist in problem solving.	2.22	2.83
Students have experience in undergraduate research.	2.28	2.94
Students have the broad education necessary to understand the impact of engineering solutions in a global/societal context (ABET - H). Students draw from their general education and science background to develop engineering solutions that demonstrate an awareness of energy, the environment, business and economics, government, and other global and societal issues.	2.11	2.50
Students demonstrate effective oral and written communication skills (ABET - G). Students will write effective documents including memos, e-mails, business letters, technical reports, operations manuals, and descriptions of systems, process, or components.	2.04	2.83

The data show that the spring 2006 cohort's final deliverables were better in every respect than the spring 2005 cohort's, despite the fact that the Sophomore Engineering Clinic II project and course were substantially identical in these two years. Thus, the improvement is likely attributable to the changes implemented in Sophomore Engineering Clinic I in the fall of 2005. Some of the outcomes in Table 6 (e.g. impact of engineering solutions in a global/societal context), while goals of the course, were not explicitly addressed by implementing the converging-diverging design model. In these cases the improvement is possibly attributable to the repetition resulting from adding the bottle rocket project, or, the progression of three projects meant students were better prepared fir the design challenges presented in SEC II, and therefore got more out of the course.

Summary

Recent offerings of the Sophomore Engineering Clinic used the Hoistinator design project as a multi-disciplinary experience in open-ended design. In an attempt to improve student

approaches to the design process, two changes to the course were made in the fall of 2005. First, the format employing semester-long projects in both the fall and the spring was replaced by a sequence of projects of increasing complexity:

1) A four week bottle rocket project that was highly constrained and primarily convergent in nature, and in which success was evaluated by a single parameter (distance flown).
2) The 10 week Hoistinator project, in which there were fewer constraints in the design space and opportunities for divergent thought, and success was evaluated by multiple parameters (cost and weight) but a single equation quantified the "quality" of the product.
3) A semester-long energy audit project in which the problem was more open ended and less well posed.

Second, the students were introduced to the converging-diverging model for design and required, in their design reports, to document specific evidence of both convergent and divergent thought. The net effect of these changes was a substantial improvement in technical performance, both on the Hoistinator project in the fall of 2005 and in a subsequent project in the spring of 2006.

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