Advances in Engineering Education

WINTER 2009

Implementing and Assessing the Converging-Diverging Model of Design in a Sequence of Sophomore Projects

KEVIN DAHM, WILLIAM RIDDELL, ERIC CONSTANS, JENNIFER COURTNEY, ROBERTA HARVEY, and PARIS VON LOCKETTE
Rowan University

ABSTRACT

This paper discusses a sophomore-level course that teaches engineering design and technical writing. Historically, the course was taught using semester-long design projects. Most students' overall approach to design problems left considerable room for improvement. Many teams chose a design without investigating alternatives, and important decisions were made without a quantitative analysis.

The faculty team addressed this shortcoming by 1) replacing the semester-long project with a sequence of design projects, and 2) presenting a converging-diverging approach to design, modeled after a paper by Dym et al. [1] Students were required to document their design approach in detail, showing specific evidence of divergent design and convergent design and specific rationale for the final decisions resulting from these processes. This paper explains the convergent-divergent design model, provides a description of the design projects, and presents a comparative assessment that demonstrates the new course organization led to dramatic improvement in student performance.

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 for each semester 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 is taught by a faculty member from Department of Writing Arts in the fall and Department of Communication in the spring, and for these faculty members, 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 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 cognitive model is an alternating series of divergent and convergent steps. One begins with a divergent, creative exploration of 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.

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

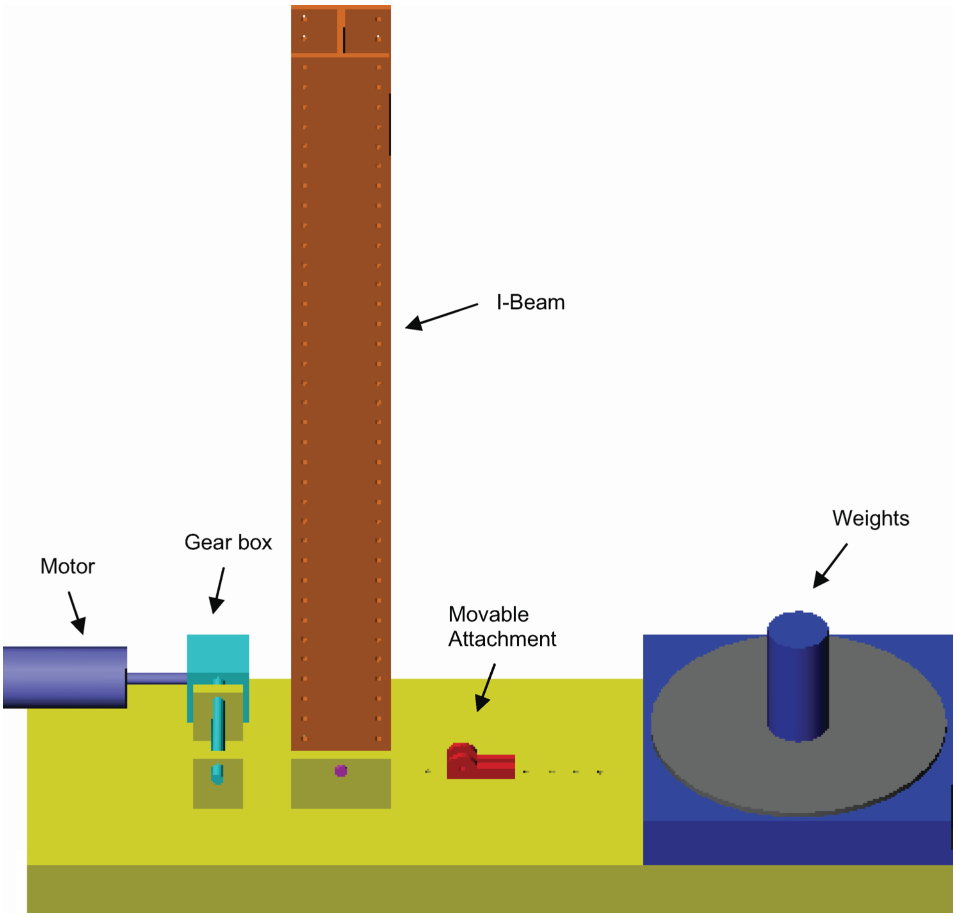

Figure 1. Substructure used by each team to support their crane.

"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.)

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 1. Substructure specifications.

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

Table 2. Structural Materials Allowed for Crane Construction.

- LCA_{p-d} is the Life Cycle Assessment Eco-indicator points, calculated by ECO-it [12] 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 was published previously [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 Engineering 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. Appendix 1 is a video of a successful lift and Appendix 2 is a video of a failure.

Question	Mean Response: 5 = strong agree, 1 = strong disagree	
	2004	**2005**
This course assisted me in developing teamwork skills	3.82	4.32
This course assisted me in developing multidisciplinary engineering design skills	3.70	4.06
This course assisted me in developing project management skills	3.93	4.24
This course helped me make the link between engineering design and writing	3.89	4.02
Number of respondents	104	108

Table 3. 2004 and 2005 student evaluations of Sophomore Engineering Clinic.

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 many cases apparently never revisited.

The above observations reflect Dym et al.'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), in effect they treated these as homework problems. Students arrived at an answer and 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 sections 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 [13, 14] and NASA has proposed standards and lesson plans for grade 5–12 students [15]. 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 1/4" 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 [16] for more emphasis on experimentation as a design activity. However, the trial and error process 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 improving their rocket's performance.

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. Copies of Dym's article were circulated and in-class discussions focused on how to apply the model of design to the project at hand. 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 as run at Rowan University was published previously [17]. Appendix 3 is a video made by one student showing the outcome of his team's first two test launches.

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 cognitive 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 reports for the Hoistinator project, students almost uniformly characterized divergent tasks as brainstorming and proposing different truss configurations, and convergent tasks as optimization of a particular truss family (force balances, determining minimum member thickness to bear a specific load etc.) These characterizations showed no deep insight but were substantially correct. The requirement of documenting convergent and divergent thinking successfully ensured that teams would, at least broadly, engage in convergent and divergent thinking.
- 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 3/4 inch to 1/2 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 3.

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 15.99, compared to means of 6.60 in Fall 2003 and 8.61 in Fall 2004. The small improvement from 2003 to 2004 may well be attributable to improvements in course organization and delivery that are normal when a project is offered for the first and second times. However, the improvement from 2004 to 2005 is far more dramatic, and cannot be attributed to lack of faculty experience with the project in 2004.

Figure 2 shows a more detailed comparison of the performance scores of the 2003–2005 cohorts. Some observations:

- In 2005, approximately 50% of teams exceeded the 2004 winning score, and approximately 70% exceeded the 2003 winning score.
- In 2005, only the bottom 20% of teams earned scores in the range of 5–6, which was the norm in 2003.

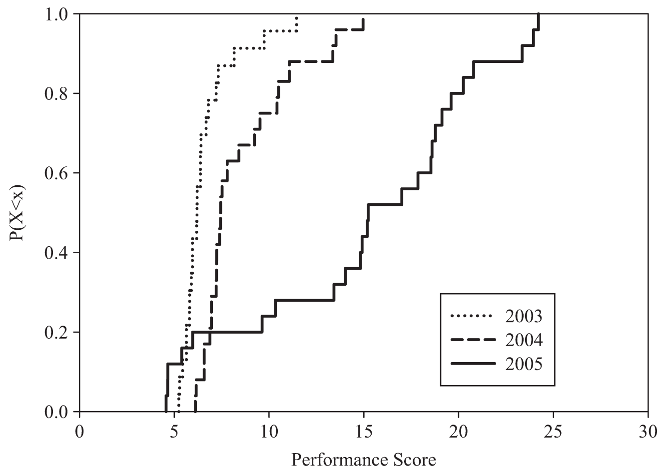

Figure 2. Comparison of performance scores for all teams in Fall 2003, 2004 and 2005 cohorts, using the 2003/2004 performance equation.

- There was very little stratification (except among the very best teams) in 2003 and 2004, while in 2005 there was a broad distribution of scores.

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 they had not seen. In addition, the 2005 students had only 10 weeks to complete the project, compared to 14 weeks in previous semesters. This suggests that the experience of a "start-up project" was indeed a better use of time than four additional weeks to work on the main project.

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 [18, 19], 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 significantly modified after the first offering in the

Cohort	Spring 2005	Spring 2006
Average SAT	1232	1230
Average HS class rank	Top 17%	Top 18%

Table 4. SAT and High School Class ranks for the spring 2005 and spring 2006 Sophomore Clinic II cohorts.

spring of 2004. However, both the project itself and the course instruction were essentially identical in 2005 and 2006, and the converging-diverging model, introduced in the fall of 2005, was NOT discussed further in the spring of 2006. The project was also led by the same faculty members in both 2005 and 2006. In addition, Table 4 shows that the 2005 and 2006 cohorts were essentially identical in high school GPA and SAT scores, these being the two metrics used by Rowan Engineering for admission decisions. In sum, the faculty did everything possible to ensure that there was no difference between the two cohorts that could affect their performance on the energy audit project, apart from their different experiences the previous semester in Sophomore Engineering Clinic I.

Assessment of the final reports from the Spring 2005 and 2006 energy audit project was conducted using rubrics that have been published in *Chemical Engineering Education* [20]. 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 [21]. 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.

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 [20] 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.

Indicator	Score 4	Score 3	Score 2	Score 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

Table 5. Sample rubric for assessment of student reports.

The data show that the spring 2006 cohort's final deliverables were better in every respect than the spring 2005 cohort's, and for some objectives the difference was statistically significant to 95% confidence. Since the instruction was substantially identical these two semesters, it is reasonable to conclude that the improvement shown in spring 2006 is attributable to the improvements made in the fall 2005 offering of Sophomore Engineering Clinic I. 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 more likely attributable to the repetition resulting from adding the bottle rocket project; in other words, the progression of three projects of increasing scope and difficulty meant students were better prepared for the design challenges presented in SEC II, and consequently performed better on the project and wrote better reports.

SUMMARY

Dym and co-authors[1] noted that most of the problems engineering students solve in an undergraduate curriculum require strictly convergent inquiry: application of math and science principles

Desired Outcome	2005	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**
Number of Reports	9	12

Boldface indicates that the difference between 2005 and 2006 performance was statistically significant (95% confidence) for that indicator

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).

to arrive at a unique correct answer. Design problems are distinct from these, as design problems are inherently unique and open-ended. Though there is no "recipe" one can follow to solve a design problem, Dym et al. assert that there are repeatable and recognizable cognitive processes that are applicable to all design problems, and propose a cognitive model for the design process as an alternating series of divergent and convergent inquiries. In this study Dym et al.'s cognitive model for design was integrated explicitly in a sophomore engineering course.

The project at the center of this study was the Hoistinator design project, a multi-disciplinary experience in open-ended design used in recent offerings of Sophomore Engineering Clinic I. Two specific 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.

There is no way to independently assess the effects of these changes individually, but the net effect of both changes was a substantial improvement in the students’ technical performance. This improvement was measured both by the objective quality of student designs and by the quality of reports describing the projects, as well as anecdotal observations. Improvement was observed both on the Hoistinator project itself in the fall of 2005 and in a subsequent semester-long project in the spring of 2006, demonstrating that the improved approach to teaching design had an impact lasting beyond the specific semester in which it was implemented.

The Bottle Rocket and Hoistinator projects were continued in the Fall 2006 and 2007 semesters. While the rigorous assessment presented in Table 6 has not been conducted for these cohorts, technical performance and anecdotal observations for these cohorts were consistent with those presented above for Fall 2005. The faculty consensus is that the structure of a 4-week project and a 10-week project, combined with presentation of the converging-diverging model of design, is effective and will be maintained indefinitely, though the specific projects offered may change.

ACKNOWLEDGEMENTS

The authors thank Rowan undergraduate students Anthony Ford and Jason Sheldon for providing the video appendices of the bottle rocket and crane projects.

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