Assessing Design Capabilities Following a Client-Based Freshman Design Course

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***Abstract* - Authentic, client-based projects form the foundation of a one-semester freshman design course at Rice University. First-year students learn the engineering design process and use it to solve meaningful problems drawn from local hospitals, local community partners, and international communities. Learning outcomes for Introduction to Engineering Design (ENGI 120) are that students design a product that meets user-defined needs and realistic constraints; communicate effectively through written reports and oral/visual presentations; and work effectively on multidisciplinary teams. Assessment of students' knowledge of the design process was measured by asking students to critique the strengths and weaknesses of a Gantt chart. Statistically significant increases are seen for topics related to needs assessment, design context review, analysis and decision-making, time allotments, and the overall layout of the design process. No changes were seen in the topics of idea generation, building and testing, and documentation. Improvements to the course aimed at achieving student learning outcomes are described.**

Index Terms - Design education, engineering assessment, first-year programs, freshman programs.

INTRODUCTION

First-Year Engineering Design Programs in Context

Design is a critically important skill in engineering practice. Sheppard and others have clearly articulated that students need to be engaged in practice-based engineering, particularly design, from the beginning of their education [1]. Learning science reveals that students learn best when there is a mixture of theoretical principles and practically-situated problems [1] [2] [3]. Thus, design and other open-ended problem solving opportunities should be integrated throughout the entire curriculum, rather than making students wait for capstone design to do "real engineering."

Forward-looking programs are providing early project-based design experiences, which simulate professional engineering practices and skills and leverage students' desire to work on challenges that impact society [2]. Currently, more than half of the top 25 U.S. engineering schools run a team-based freshman design course providing students with real-world engineering opportunities. At some universities this experience is mandatory for all first-year engineering students, while other programs offer discipline-specific design experiences. With learning science as a foundation, a team-based design course can build on best practices: collaborative learning, authentic and socially motivated projects, and social interdependency [1] [4].

Educators are also strongly focused on reducing overall attrition and gender- and ethnic-specific inequalities [5]. Creating an engaging, student-centered environment is vital for retention of all students, especially women and members of underrepresented groups [2] [6]. Retention rates vary, but average values are typically cited as 50-60% [7]. Numerous studies have shown that student attrition from engineering is largely driven by the perception of an unwelcoming and unmotivating learning environment [2]. Classrooms that support interactions, such as in-class discussions and collaborative learning environments, can counter these perceptions and can improve students' self-confidence and self-efficacy [8]. A long-term study from the University of Colorado Boulder (UCB) indicates that students who participated in a freshman year experience showed retention rates 19% higher than a control group (measured at seventh semester) [9]. Even higher gains in retention are observed for women and ethnic minorities.

First-Year Engineering Design at Rice University

At Rice University, there has not been a strong history of first-year programming for engineering students. Presently, there is no required engineering course for first-year students. Typically, students take mathematics, physics, chemistry, and elective courses during the first year.

In the past two years, two important resources, namely the Oshman Engineering Design Kitchen (OEDK) and the Rice Center for Engineering Leadership (RCEL), have been initiated and developed. These two resources enabled Rice University to develop Introduction to Engineering Design (ENGI 120), a popular client-based freshman design course.

The OEDK provides a space where undergraduate students from each of the eight engineering departments work collaboratively on real-world, multidisciplinary design challenges. The OEDK houses a large central work area that holds 36 individual work benches, three conference rooms, a flexible classroom, a computer lab, a wet lab, and a machine shop. The OEDK also maintains several pieces of rapid prototyping equipment, including a 3D ABS plastic printer, a laser cutter, soldering station, and a printed-circuit board mill. The OEDK is also well stocked with machining equipment and tools that can be used by any of the teams to complete their projects. Two technical staff members assist students as they develop their design solutions.

RCEL was established in 2010 to prepare engineering students to become effective leaders by leveraging their technical expertise, an entrepreneurial spirit, and persuasive communication skills to solve challenging problems. RCEL provided the seed funding to launch ENGI 120 as well as the complementary courses associated with it. In addition, RCEL supports many of the faculty who contribute to teaching the course.

DESCRIPTION OF ENGI 120 COURSE

ENGI 120 Course Content

Introduction to Engineering Design (ENGI 120) is a one-semester design course for freshman students at Rice University. The course is an elective course available for all freshman students in the School of Engineering. Enrollment is currently limited to 40 students each semester. The textbook for ENGI 120 is Engineering Design: A Project Based Introduction [10]. The course was offered for the first time in spring 2011 and has been offered every semester since then.

The objectives for ENGI 120 are to (a) have students learn and practice the engineering design process early in their engineering education, and (b) increase undergraduate retention in engineering at Rice University by 10%. While these objectives are written specifically for Rice University and for ENGI 120, these two objectives align with important themes published elsewhere [1] [2] [11].

Three specific learning outcomes were established to reach course objectives:

(1) Students design a product that meets a user-defined need and realistic constraints. Specifically, students develop realistic design criteria, apply appropriate methods for brainstorming to generate multiple design solutions, use decision matrices to select among design solution options, and iteratively prototype a physical product.

(2) Students effectively communicate progress of their design using written and oral/visual communication.

(3) Students function effectively on a high-performance team.

The design methodology used in ENGI 120 is shown in Figure 1. Steps in the design process form the core of the lecture material (Table I). During the first half of the semester, each 75-minute class period is divided into two segments. In the first 30 minutes, the class meets as a whole group for an interactive lecture on a step in the design process or an important skill such as writing technical documents or teamwork. During the remaining 45 minutes, students meet in their design teams. The first half of the semester is devoted to defining the design problem, developing the design context review, establishing design criteria, brainstorming solutions, using an evaluation matrix to select a solution, and then describing the selected solution. The allocation of class time changes mid-semester. In the second half of the semester, there are a few lectures on the role of failure in the design process, prototyping, and testing, but most class time is set aside for teams to work on their projects in the OEDK.

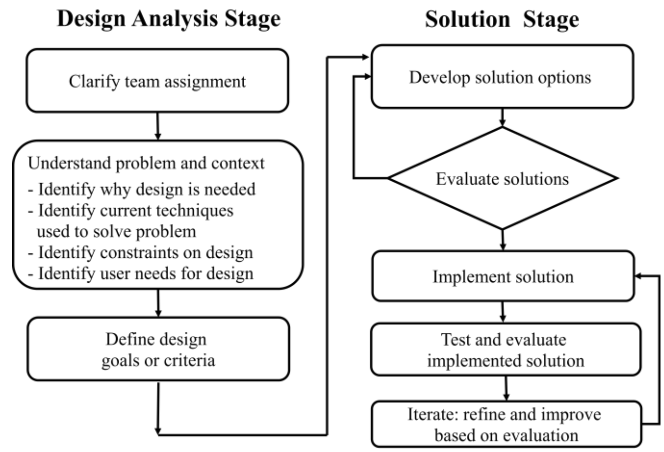

FIGURE 1
DESIGN PROCESS IMPLEMENTED BY STUDENTS IN ENGI 120

TABLE I
LECTURE TOPICS IN ENGI 120

In-class Lecture Topic	In-class Lecture Topic
Course introduction	Methods to evaluate design solutions
Introduction to design challenges	Oral presentations & graphs
Design process overview	Prototyping, fasteners, and supplies
Defining the design problem	Testing design solutions
Preparing written reports	Role of failure in design
Search tools	Project planning and Gantt charts
Design criteria	Manufacturability
Teamwork	Environmental issues
Brainstorming	

Client-Based Projects in ENGI 120

ENGI 120 students learn the process of engineering design by solving authentic problems proposed by clients from medicine, industry, humanitarian organizations, and Rice University. The instructor, in collaboration with other Rice faculty, networks with potential clients and works with them to develop projects that are appropriate in terms of scope and complexity. The most appropriate design projects are based on a genuine need; are open-ended with many possible solutions; do not require discipline-specific knowledge; and afford the opportunity to build and test prototypes.

Table II lists projects and their sponsors for the first three semesters. Due to Rice University's proximity to the Texas Medical Center, many projects come from clients in the medical field. We have also partnered with the student-led Engineers Without Borders (EWB) group and with Rice's Beyond Traditional Borders (BTB) program, which focuses on developing global health technologies.

Each team works on a different client-sponsored project, with four to six students per team. During the first week of class, students learn about the projects, rank their top five choices, and describe their prior experiences with tools, computers, and design. The instructor assigns students to teams based on students' project preferences and skills as well as team diversity.

TABLE II
PROJECTS IN ENGI 120

Project Topic	Client/Sponsor
Spring 2011	
Wheelchair modification	Shriners Hospital
Measurement of forearm rotation	Shriners Hospital
Water irrigation system for green roof	OEDK building manager
Modification of surrey bicycle	Rice Facilities Engineering and Planning (RFE&P)
Fall 2011	
Object grabber	Shriners Hospital
Alternative materials for sidewalks	RFE&P
Novel hose design to water trees	RFE&P
Improving classroom acoustics	OEDK building manager
Collapsible medical exam bed	EWB (Rice)
Limited IV volume from 1L bag	BTB (Rice)
Engineering and science demonstration	Wilson Elementary School
Training mannequin for nursemaid's elbow reduction	Texas Children's Hospital
Spring 2012	
Improved goniometer	Dynamic Orthotics and Prosthetics
Evaporator for groundwater derived waste	Shell Oil Company
Giraffe hay feeder	Houston Zoo
Puzzle feeder for orangutans	Houston Zoo
Low power alarm for bCPAP	BTB (Rice)
Continuous water purification system	EWB (Rice)
Dressing aid	Shriners Hospital
Measurement of bicep and triceps strength	OrthoIntrinsics

Once students have been assigned to projects, they meet with their clients to clearly define the problem and set design criteria and constraints. The teams continue to have occasional contact with clients via email or meetings, and clients usually attend the two oral presentations.

Two projects are described briefly. In fall 2011, a team designed an accurate and precise mechanism to regulate the total volume of IV fluid that is titrated from a 1-L IV bag. The design includes a counterweight system and a mouse trap that kinks the IV tubing once the correct volume of fluid has been dispensed [12]. The device is rugged and costs less than $20 to construct. Designed for use in developing countries, this device can prevent overhydration in children receiving IV therapy. During the summer of 2012, this device is being field tested in Malawi through the BTB program.

In spring 2012, a team built a safe and sturdy hay feeder for the giraffe herd at the Houston Zoo [13]. Complete with imitation "branches," the new hay feeder extended the feeding time for the giraffes from approximately 3-4 hours to 12 hours, in line with the zoo keeper's primary design criterion for the project. Work is ongoing to improve the aesthetic appeal of the design prior to its full deployment at the zoo.

Course Assignments for ENGI 120

Documentation is an important, on-going part of the design process. Teams submit a series of technical memos (TM) and one executive summary to communicate their progress. Each technical memo focuses on a key aspect of the design process (Table III). The executive summary concisely captures work from the entire semester.

During the semester, each design team gives two 15-minute oral presentations, each of which is delivered by one team member. The first oral presentation covers the design problem and its relevance, background on existing solutions, design criteria, several feasible design solutions, the process to evaluate design solutions, and the design solution(s) ultimately selected. The second presentation emphasizes the rationale for the working design and its features, prototype(s) built and their demonstration, testing of prototype(s), successes and limitations of existing design, progress toward the design criteria, and future work. In addition to formal presentations, the teams undergo two prototype checks and one final graded prototype evaluation.

TABLE III
TECHNICAL MEMO AND ORAL PRESENTATION ASSIGNMENTS

Assignment	Assignment Topic
TM 1	Problem statement
TM 2	Design context review and bibliography
TM 3	Design criteria
TM 4	Brainstorming of design solutions
TM 5	Evaluation of design solutions
TM 6	Final design plan
Oral Presentation I	Summarizes work that led to proposed design
TM 7	Testing plan
TM 8	Progress report
TM 9	Progress report
Oral Presentation II	Summarizes the final design and testing
Executive Summary	Summarizes work from entire semester

Peer evaluation is conducted three times during the semester using the online CATME system [14]. CATME assesses student performance in their team along five dimensions including interacting with the team and having related knowledge, skills and abilities. The final individual team participation grade is based on technical contribution, peer evaluation, instructor evaluation, and self-evaluation. Student grades are assigned according to the proportions documented elsewhere [15].

Support for ENGI 120 Teams

Each team works with a faculty mentor who offers technical expertise and encouragement. Faculty mentors may teach fundamental engineering concepts, direct students to other resources, and assist with troubleshooting. Teams interact with their mentors on a weekly basis for 15-20 minutes throughout the semester.

Upper-class engineering students also work with the freshman ENGI 120 teams during and outside of class time. The Apprentice Leader program is described elsewhere [15] and is currently undergoing modifications. Upper-class engineering students support the freshman to develop their technical writing, oral presentation, and prototype fabrication skills. Upper-class students hold office hours to support these activities.

ASSESSMENT OF THE ENGI 120 COURSE

Student Surveys and Retention

Surveys of ENGI 120 students were administered at the end of three semesters (spring 2011 for 20 students, fall 2011 for 44 students, spring 2012 for 37 students). Student perception of improvements in skills, including engineering design, problem solving, and teamwork, as well as self-efficacy toward engineering were examined [15]. These data are self-reported, and may not reflect actual improvement in skills. Survey results indicated that freshman students thought ENGI 120 helped them develop skills in engineering design, prototyping, and writing and editing technical documents. ENGI 120 improved students' desire to select an engineering major and helped establish community. While early in the program, student self-reported retention in engineering is approximately 90% [15].

Direct Assessment of Students' Design Knowledge

Assessing students' ability to recognize and analyze the key steps of the design process is an important yet challenging task [16] [17]. A variety of assessment methods have been used in first-year design courses including surveys, interviews, talk aloud protocols, concept maps, exams and written reports, as well as the evaluation of students' final design prototypes [17] [18]. Each of these methods has well documented limitations [17] [18]. Combining several methods to cross-validate results compensates for these limitations; however, triangulating and analyzing multiple sources of data require considerable time and resources.

Bailey and Szabo's Gantt chart tool is a valid, feasible option to assess individual design process knowledge [17] [19] [20]. Using this tool, pre- and post-testing of ENGI 120 students' knowledge and application of the design process was conducted. Specifically, students were asked to critique the strengths and weaknesses of a Gantt chart laying out a 14-week design process (Figure 2). Studying students' evaluations of a Gantt chart may not provide a complete representation of students' design process knowledge; however, this approach has been shown to identify gaps in students' understanding [17].

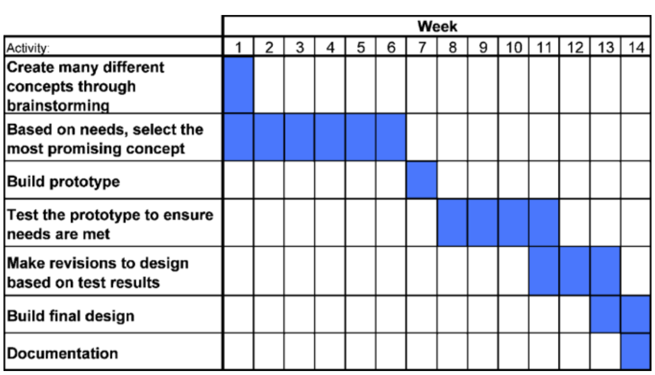

FIGURE 2
GANTT CHART FOR ASSESSMENT OF STUDENTS' DESIGN KNOWLEDGE

For both the pre- and post-test, students were given the prompt: "Critique the proposed design process, as displayed in the Gantt chart. Identify the pros (advantages, strengths, etc.) and cons (disadvantages, weaknesses, etc.) of the proposed design process lasting 14 weeks." Students were given supplemental material about Gantt charts so that their ability to complete the assignment was not limited by their knowledge or experience with Gantt charts. Students uploaded a written document (typically ½ to 1 page in length) into the online course management system.

In fall 2011 and spring 2012, the pre-test was administered during the second week of class as a take-home assignment. At this point, the students had been exposed to a 30-min lecture introducing the overall design process (Figure 1). The post-test was administered as a take-home assignment during the final exam period. At this point, all students had gone through the design process with a client-based project. Students received extra credit (3 points) on their final grade for completing both the pre- and post-test.

Students' responses were scored against the eight topics listed in Table IV. To analyze the data, all identifying information was removed from the pre- and post-test responses, and they were randomized. Three trained raters used a scoring rubric created by the course instructor to assess the responses, scoring each of the eight topics on a three-point scale (0, 1, 2). (The starting points for developing our rubrics were rubrics published by Bailey and Szabo [17] [19].)

Given this three-point scale, a score of 0 indicated no mention of a topic at all. For Topics 1-6 and 8, a score of 0 also indicated a statement that reported only the amount of time designated for that topic in the Gantt chart. A score of 1 indicated some mention of the topic and what the task entails. A score of 2 represented an appropriate critique supported by correct reasoning.

To illustrate examples of student responses on the established 0-2 scale, quotes from students on Topic 4 (analysis and decision-making) are given:

Score of 0: *"A strong emphasis is placed on selection of the most promising concept (6 weeks).*"

Score of 1: *"Also, I noticed it took 6 weeks for them to pick a concept. I think that is way too long. I think it should take less than half the time to pick the concepts and go through their advantages and disadvantages."*

Score of 2: *"While the brainstorming step will most likely last for a week or less, selecting the appropriate design to pursue will not last 6 weeks. The team will likely go through a series of Pugh matrices to select which solution they would like to pursue after comparing each of them to previously-defined design criteria.*"

Samples for both semesters were combined. The sample size for the pre-test was 68 (of 81 students), giving a response rate of 84%. The sample size for the post-test was 67 (of 81 students), giving a response rate of 83%. Because the data distribution was non-normal, a permutation test was conducted to check for differences between pre- and post-test responses for each topic. We first computed the value of the test statistic, M_0, as the difference between the post- and pre-test mean. Then, repeating 10,000 times, random permutations of the data (randomly rearranging the pre- and post-testing labels) were performed and the corresponding test statistic M_k was calculated for each time. The approximate P value was the percent of the test statistics of which the absolute value was greater than $|M_0|$.

Students' knowledge and application of the design process have improved in some areas through their ENGI 120 experience (Table IV). Statistically significant increases in student knowledge of engineering design were seen for five topics:

1 - Needs assessment/Establishing design criteria,
2 - Design context review,
4 - Analysis and decision-making,
6 - Overall layout of a design process and iteration, and
7 - Time allotments.

Topics 1, 2 and 4 were important topics in the course and were reinforced through technical memo and oral presentation assignments. Topics 6 and 7 were embedded in the course's structure.

TABLE IV
ASSESSMENT OF DESIGN KNOWLEDGE AND APPLICATION

	Topic	Pre-test ^	Post-test^	P value#
1	Needs assessment/Establishing design criteria	0.36 ± 0.50	0.67 ± 0.70	<0.001
2	Design context review	0.47 ± 0.67	0.85 ± 0.80	<0.001
3	Idea generation	0.63 ± 0.70	0.77 ± 0.74	<0.1
4	Analysis and decision-making	0.38 ± 0.42	0.80 ± 0.79	<0.001
5	Building and testing	0.97 ± 0.43	1.05 ± 0.50	>0.1
6	Overall layout of a design process and iteration	0.92 ± 0.75	1.46 ± 0.64	<0.001
7	Time allotments	1.72 ± 0.51	1.86 ± 0.35	<0.005
8	Documentation	1.23 ± 0.93	1.23 ± 0.91	>0.5

^ Data reported as mean ± standard deviation. #P value is two-sided.

After completing the course, students articulated the importance of design criteria and their role in selecting an appropriate design. This improved understanding impacted Topics 1 and 4. At the end of the course, many students also recognized that completing a design context review was missing from the Gantt chart; this recognition was scored in Topic 2. Post-test responses about the iterative nature of the overall design process (Topic 6) reflected a more realistic understanding, including references to concurrent testing and revisions and unexpected setbacks.

Students scored highest on time allotments (Topic 7) on their pre- and post-test responses. To achieve a score of 2 on this topic, students had to correctly identify at least one specific problem with the allocation of time for the various activities in the Gantt chart. Many students recognized that six weeks was too much time to devote to evaluating potential solutions or that one week was not enough time to build a prototype.

No statistically significant differences were seen for three other topics:

3 - Idea generation,
5 - Building and testing, and
8 - Documentation.

Idea generation or brainstorming (Topic 3) and building and testing (Topic 5) were also important topics in the course, although students failed to show improvements in these areas. Many pre- and post-test responses received scores of 0 on the topic of idea generation because students analyzed the Gantt chart and simply reported that setting aside one week to brainstorm would be sufficient without any discussion of what brainstorming was or why it's useful.

Building and testing (Topic 5) scores hovered around 1 on pre- and post-test responses. Students noted that these two activities would require more time to ensure that a prototype worked, but few mentioned that testing was important in determining whether a prototype satisfied a set of design criteria or user needs, which was required to earn a score of 2.

The importance of documentation (Topic 8) and its sequencing throughout the ENGI 120 course were evident in the syllabus design and strongly emphasized during the first week of class. This early exposure may have influenced students' higher pre-test responses.

The mean post-test values for Topics 1-4 were less than 1.0 on the established scale of 0 to 2. Post-test values for Topics 5, 6 and 8 were all between 1.0 and 1.5. Only Topic 7 was greater than 1.5. Overall, the absolute magnitude of these scores was lower than expected.

Tests for inter-rater reliability were conducted for each topic using an unweighted method. Fleiss' Kappa value was >0.8 for Topic 8, >0.6 for Topics 1 and 2, >0.4 for Topics 3-6, and >0.3 for Topic 7 [21]. These values may be a slight overestimation since the ordered nature of the data was not accounted for directly. However, considering the scores not in agreement, no more than 10% were in disagreement by 2 points; thus, this approximation may be reasonable. Overall, inter-rater reliability varied considerably in this preliminary study.

In summary, this direct assessment can be used to evaluate student performance against learning outcome (1): "Students design a product that meets a user-defined need and realistic constraints. Specifically, students develop realistic design criteria, apply appropriate methods for brainstorming to generate multiple design solutions, use decision matrices to select among design solution options, and iteratively prototype a physical product." Overall, students are meeting this learning outcome and show statistically significant improvement in five of the eight areas probed in design process knowledge. However, by looking at the absolute values of the post-test values and the areas where students do not demonstrate statistically significant changes, clear opportunities remain to improve student performance.

FUTURE WORK

Overall, this course is working smoothly, and students regard it as a fun and popular elective. However, in the future, we are planning some adjustments to the course. Specifically, we will transfer some of the delivery of the content knowledge about the design process to an on-line format. The authors will make short, engaging videos about topics from Table I for students to watch prior to coming to class. Then, during class time, more time can be devoted to active learning exercises. This will give students extra time to practice the design process, as well as time to think critically about and evaluate other design challenges. We expect that this will improve their performance using the direct assessment tool.

We also want to change the method used to collect the Gantt chart assessment data. Specifically, we will adjust the timing and stakes associated with the pre- and post-test exercises. The pre-test exercise will be administered on the first day of class to minimize students' prior exposure to design process knowledge. The post-test exercise will be posed as a question on the final exam to incentivize students to provide more thorough analyses.

CONCLUSIONS

Authentic, client-based projects form the foundation of a one-semester freshman design course at Rice University. Assessment of students' knowledge of the design process was measured by asking students to critique the strengths and weaknesses of a Gantt chart. Statistically significant increases were seen for topics related to needs assessment, design context review, analysis and decision-making, the overall layout of the design process, and time allotments. No changes were seen in the topics of idea generation, building and testing, and documentation. Implementing and overseeing a client-based freshmen design course is time-consuming and resource-intensive, but the students are actively engaged in the design process and derive great satisfaction from solving a problem and producing a prototype for a client. In addition, this experience prepares students for the client-based design projects that all Rice engineering students take during their two-semester capstone design course.

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