Design/Build Projects in an Introductory Engineering Course

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***Abstract* - A comprehensive design/build project has been incorporated into the introductory engineering course at Bucknell University. Working in teams of four, students address real design objectives, work with real customers, accommodate real constraints, construct a working prototype of a device, and demonstrate it at a public exposition attended by teachers, scout leaders, and 10-year-old children. The project requires students to address essentially all elements of the engineering design process, construct from raw materials a working device, and interact effectively with end users at the exposition.**

Index Terms – Introductory engineering course, design projects, engineering design process

INTRODUCTION

The first engineering course offers an opportunity to provide an early introduction to a formalized engineering design process, but it is a process with important nuances, constraints, challenges and obstacles that often arise from shifting client or customer demands, and inevitable uncertainties. It is a process that requires systematic, objective decision-making but with agility: an ability to recover from failure or changing expectations and cycle back through the design process while remaining responsive to the client or customer, and addressing the challenges of product value and manufacturability.

A comprehensive design/build project has been incorporated into the introductory engineering course at Bucknell University. Working in teams of four, students address real design objectives (educational standards), work with real customers (scout leaders and college education majors immediately prior to their student teaching semester), accommodate real constraints (financial, manufacturability, safety, portability, etc.), construct a working prototype of a device to meet specific design objectives (described below), and demonstrate it at a public exposition attended by teachers, scout leaders, and 10-year-old children and their parents. The project requires first-year engineering students to address all elements of the design process, fabricate a working device, and interact effectively with their product's end users: 4th-grade teachers, scout leaders, and 10-year-old children.

The first engineering course begins with an introduction to the engineering profession, the different engineering disciplines, and the engineering design process. Students then select and are enrolled in the first of three, three-week discipline-specific seminars offered at intervals during the semester. Nine seminars are offered and no more than two are offered in any one discipline, so students will experience at least two engineering disciplines in some depth by the conclusion of the course. Following the first seminar session, one week of the course is dedicated to an introduction to professional ethics; this segment extends from morality to ethics, and includes several case studies and application of the National Society of Professional Engineers Code of Ethics for Engineers [1] in a case analysis.

The segment is followed by the second seminar session, and in the week following that session the students are formed into teams of four to begin the final design/build project in the course. In that week, students are introduced to the project, the project design goal, and their customers. At the end of that week, the teams are expected to have developed refined objectives, constraints and criteria, developed the concept for at least three alternative designs, applied a selection process using decision matrices, and proposed a single design alternative for detailed design and fabrication. This work is reported in writing by each team to their faculty adviser and primary customer representative who review and prepare feedback that is provided to the teams at the end of the third seminar session. Following meetings between design teams and customers, the students have approximately two weeks to complete the detail design of their project, build it, test it, and demonstrate its operation to their faculty adviser. Each project is demonstrated to a larger audience of children, teachers, education majors, and scout leaders at a final exposition.

An important aspect of the final design project is that the design process is intentionally decoupled from the technical content of the project. First year engineering students typically have sufficient background knowledge in the subject area that little additional research is necessary, and the students can focus instead on the design process itself. By lowering the technical expectations for the project it also becomes possible to assemble multidisciplinary project teams with students from diverse backgrounds and with differing levels of preparation.

PROJECT OVERVIEW

The United States is facing an expected shortage of engineers as the needs of high-technology sectors grow, the world's population increases, the infrastructure deteriorates in many developed countries, developing countries face a growing need for new infrastructure, and the fraction of first-year college students electing to major in engineering remains small. A logical approach to this problem is to foster experience with and interest in engineering among youngsters, who might then pursue an engineering degree when they enter college. In order to teach the foundations of engineering, elementary and secondary school teachers of science and math, and youth group leaders, can benefit from being able to use hands-on, interactive educational devices in their programs. This is particularly true for concepts that are difficult to understand without a demonstration. Therefore, there is a need for the development of appropriate educational tools that teachers and others who work with children can use to introduce their students to science, technology, engineering and math (STEM).

In the final design/build course project, teams of four students are tasked with designing and building an ***educational device*** that will enable children of approximately 10 years of age to explore and learn an engineering or scientific principle. The student teams are assisted in this project through the interaction with actual customers: third-year Bucknell University education majors and Scout leaders and parents. Student teams are partnered with a customer or customer team who provide guidance on what is appropriate for children and provide feedback on the appropriateness and effectiveness of device designs.

Design teams are assigned an educational objective derived from the Commonwealth of Pennsylvania Academic Standards for Science and Technology [2] or the Cub Scout Webelos Activity Badge Requirements [3] as the educational objective for their device. In the creation of the device, the engineering design process is followed. While commercialization of the device is beyond the scope of the project, a working educational device that has been designed so commercialization would be feasible, including ease of fabrication and the use of readily-available materials, is required.

The Design Process

In the course, engineering design is defined as a creative yet structured decision-making process, often iterative, in which knowledge is applied to convert resources to optimally achieve a design objective.

The formalized process used in the course consists of ten steps:

1. Identify the problem
2. Research and gather data
3. Establish design goals, criteria, and constraints
4. Identify potential alternative solutions
5. Evaluate potential alternative solutions
6. Develop and test models
7. Select the best alternative
8. Communicate and specify for implementation
9. Implement and/or commercialize
10. Perform post-implementation assessment

In the final design/build project, all 10 steps of the design process are addressed and completed by the student teams.

Design Objectives: Educational Standards and Scout Achievement Requirements

Design teams are assigned one of three selected educational objectives derived from the Commonwealth of Pennsylvania academic standards for engineering and technology or the Cub Scout Webelos activity badge requirements. The objectives are listed below:

From the Pennsylvania Academic Standards –

3.4.4.B Know basic energy types, sources, and conversions.

- Identify energy forms and examples (e.g. sunlight, heat, stored, motion).
- Know the concept of the flow of energy by measuring flow through an object or system.
- Describe static electricity in terms of attraction, repulsion, and sparks.
- Apply knowledge of basic electrical circuits to the design and construction of simple direct current circuits.
- Classify materials as conductors and nonconductors.
- Know and demonstrate the basic properties of heat by producing it in a variety of ways.
- Know the characteristics of light (e.g. reflection, refraction, absorption) and use them to produce heat, color, or a virtual image.

3.4.4.C. Observe and describe different types of force and motion.

- Recognize forces that attract or repel other objects and demonstrate them.
- Describe various types of motions.
- Compare the relative movement of objects and describe the types of motion that are evident.
- Describe the position of an object by locating it relative to another object or the background (e.g. geographic direction, left, up).

3.6.4.C Know physical technologies of structural design, analysis and engineering, finance, production, marketing, research and design.

- Identify and group a variety of construction tasks.
- Identify the major construction systems present in a specific local building.

- Identify specific construction systems that depend on each other in order to complete a project.
- Know skills used in construction.
- Identify examples of manufactured goods present in the home and school.
- Identify basic resources needed to produce a manufactured item.
- Identify basic component operations in a specific manufacturing enterprise (e.g. cutting, molding, joining).
- Identify waste and pollution resulting from a manufacturing enterprise.
- Explain and demonstrate the concept of manufacturing (e.g. the production of a tennis racket or a ball point pen).
- Identify transportation technologies of propelling, structuring, suspending, guiding, controlling and supporting.
- Identify and experiment with simple machines used in transportation systems.
- Explain how improvements in transportation systems have changed society.

From the Cub Scout Webelos Activity Badge Requirements

- E5. How is electricity generated, how does it get to my home?
- E6. Electrical circuits – Create/build/complete an electrical circuit. What are the necessary components for this to work?
- E7. What are the different types of bridges, why are they different, how do they work, and how are they built?
- E8,9. Lifting, throwing, mechanical advantage and conservation of energy – Create/build/demonstrate how forces may be transmitted through a system to make a given task easier or possible.
- S1. What is Bernoulli's principle, how does it work, what does it mean, and how do we apply it?
- S3. What is inertia, how does it work, what does it mean, and how do we apply it?
- S5,6,7. What is pressure, how does it work, and how do we apply it?
- S8. What is Newton's 3rd Law, what does it mean, and how do we apply it?
- S11. What is "center of gravity," what does it mean, and how do we apply it?

Design Constraints and Criteria

Several design constraints are identified in the project statement, as listed below. These constraints are intended to increase the feasibility that the device will be used in the classroom by a teacher or implemented by a scout leader. The design teams are expected to operationalize the constraints (i.e. as the device must be "portable," what limits on size, weight, and number of components does that entail?). Additional constraints may be introduced by the design team's customers. The design teams are also asked to develop a list of design criteria (such as the device's interactive potential and its attractiveness to youngsters) to guide their development of conceptual design alternatives and evaluate their effectiveness.

- The device must be something a teacher or scout leader can use to demonstrate a concept within an assigned state educational standard or scout achievement requirement to a group of young people within approximately a 15-minute time period.
- It may be a physical object or assembly of physical objects.
- The device must be **safe** to use with and around children.
- The device cannot create a mess that would not be easily cleaned up with a single paper towel.
- The device must be portable.
- The device must be sturdy enough to withstand multiple transports and setups by adults, and multiple uses by children.
- The materials from which the device is constructed must cost no more than $100. There is no limit on the cost of fabrication, but each student team must successfully complete the fabrication with some limited assistance from technical staff, primarily in cutting or otherwise forming materials to size.
- The device is permitted to use electricity from an outlet (120V only). It *cannot* require running water, but it *can* use water in small quantities provided from bottles.

Budget, Materials and Fabrication

Each student team has a materials budget of $100. Student teams are limited to the use of commercially-available materials. Materials difficult to transport or acquire within walking distance of the campus, such as lumber, plywood, and PVC piping, are provided by the university to the student teams without charge, but their costs must be accounted for in their project budgets and are subject to the $100 maximum. Other materials and services needed, such as poster board and printing of display documents, are provided without charge. Each team is expected to designate a treasurer within the team; he or she is responsible for collecting receipts for materials purchased, and reimbursing other team members who have made receipted purchases. At the end of the project, the treasurer is reimbursed from the course operating budget up to the maximum of $100 for all receipted purchases.

Fabrication is undertaken by the student teams. Potentially dangerous power tools (table saws, miter saws, etc.) are operated by technical staff or trained faculty at the direction of individual student teams. The engineering college machine shop, associated spaces, and technical staff and faculty, are available to the students in the week following the Thanksgiving recess during both afternoon and evening hours.

Project Schedule

All of the students in this introductory course have expressed an interest in engineering but approximately one-third of them have not selected a particular discipline. Therefore, project teams are formed by arbitrarily designating four students to constitute each team. The size of the teams is small enough that the contributions of each member are vital, but large enough to provide some degree of inter-rater reliability in their final peer assessments [4].

The design cycle for the final project spans roughly six weeks from the formation of design teams until the public presentation of their projects. During the first week the design teams meet with their respective customers and develop an understanding of the particular educational needs of children in the target age group. The faculty advisor presents the constraints imposed upon them by the course, and each team works to create several potential design solutions. At the end of the first week the student teams must submit an initial design proposal that includes descriptions of three conceptual designs along with an analysis of the feasibility of each design. The students are taught to evaluate competing design proposals using a decision matrix, and their choice for the final design must be justified using the results of a decision matrix that they create based on their understanding of the design constraints and priorities. This choice must also consider the initial feedback from both their customer and faculty advisor. For their selected design the group must present an initial abstract for the device and its capabilities along with a sketch of their concept for the prototype. The sketch must label all key parts, convey some sense of how the device will move (if it does), list the materials used in its construction and specify what utilities (electricity, heat, etc.) are required, if any.

After the first week, which is devoted to the design project, the students enter their third and final seminar rotation. During these three weeks the faculty advisors and customers review the design proposals submitted by each project team and provide written feedback to them. In particular, the faculty advisors identify those proposals that do not appear to meet the course goals or have significant technical problems. In those cases the faculty advisor meets with the project teams as necessary to refine, and sometimes completely redefine, their project plans. Any materials or components that are not readily available are identified and ordered, or suitable alternatives are found.

The student teams meet with their customers again at the first course session after the third seminar and informally present their design proposals. Any modifications suggested by the customer are taken into consideration and at this point the students are expected to be prepared for project fabrication. This customer meeting is typically scheduled just before the Thanksgiving break, and each team is required to compile a list of necessary materials before the break. Since first year students often do not have their own vehicles on campus the faculty advisors use the break to collect any materials that would be difficult for the students to obtain and transport themselves, such as sheets of plywood, lumber, and plastic pipe.

When the students return from Thanksgiving break they immediately begin to fabricate, assemble, and test their devices. Additional staffing and extended hours for the engineering fabrication shops are provided during this period to ensure that power tools and machines are used safely and effectively. Faculty advisors are also available as necessary to help the students respond to unexpected design problems. Each student team is required to informally demonstrate a working device to their faculty advisor before the end of the first week after Thanksgiving break.

Having successfully designed, fabricated, and demonstrated their device, the students are given several days to prepare their presentations for the Expo. One important element of the presentation is the project poster, which must include a description of the device, a bill of materials with cost information, and a clear definition of the technical principle that is being demonstrated. The students are also required to provide a written set of instructions that would enable an elementary school teacher to replicate the demonstration and explain how it relates to the chosen technical principle. In addition to this written information, the students must be prepared to demonstrate their device. Ideally, the students will be able to engage their target audience in the demonstration as well.

The Expo

The Expo is a lively, exciting finale to the project that benefits the students and the community. Each student group is required to set up a small booth with their device, a poster board explaining their device and documentation that includes the bill of materials, a description of the technical background for their device and instructions on its use. Local 4th grade teachers, scout leaders, 4th grade students, and parents are invited to attend the Expo and take home a student group's device at the end of the night. Thus, the devices are able to provide an educational experience to children as were their design intention.

The project could end with a standard presentation to fellow students and faculty. This standard procedure would allow students to see their peers' final product while also allowing faculty to grade the students' achievements in a standard format. However, the expo allows this to occur while also engaging the community and forcing the students to present the capabilities of their device to those who could be interested in buying a device that demonstrates a pertinent scientific principle to their children or 4th grade students. This process generates greater engagement for the students for they must sell the capabilities of their device to real potential customers, including teachers, scout masters, parents and children, while still allowing faculty to question students on their design and help them to realize the benefits and deficiencies of both their product and their ability to work through the design process. Students must demonstrate how their device works in a comprehensible manner to both adults and children and explain how it helps children to achieve the associated educational standard. During these student demonstrations faculty mingle among the intended audience to grade each design team on a rubric that assesses the project on the following:

- Poster - clarity of written elements, clarity of visuals, explanation of concept, completeness and accuracy.
- Presentation - Clarity of explanation, “sales pitch,” demonstration of device function, group participation (all design team members are required to participate in demonstrating and explaining the device, and in assisting the customers in its use), and professionalism (conduct, appearance).
- Device – Functionality, repeatable functionality and durability, effectiveness in demonstrating/teaching the concept it is intended to teach, appropriateness for the age of the intended customers.

The Expo has received excellent feedback from the students and the community. The students find the opportunity to engage with their intended audience rewarding, while the community invitees appreciate the work the students have done to help their children’s educational development in a fun and exciting manner.

Initial submittal of conceptual alternative designs and selection

The faculty adviser reviews the document and returns it to each group with extensive feedback during the final seminar. In preparation for the next class on the final project that occurs after the third seminar is complete, each group must bring a revised copy of their final design based on their given feedback. The device with revisions must be approved by the faculty advisor before construction on the device can begin.

Detailed Bill of Materials with Prices

A bill of materials is an itemized list of all of the raw materials that went into the production of an item, along with the price and source of each. This information is presented in a table or a nicely-formatted Excel spreadsheet.

Teacher Instructions

Each team is required to generate step-by-step easy-to-follow instructions for use of their device. Diagrams with dimensions and labels are required.

Technical Background

As teachers and scout leaders may not have had significant coursework in the particular area addressed by the educational device, a short (one page or less) description of the technical background that a person needs to understand how the device works and what it does is required.

Poster requirements

A 34” x 44” poster is required at the expo. The purpose of the poster is to explain and “sell” the device and demonstration to the attendees. At a minimum, the poster should provide the educational objective of the device, background on the engineering involved, an explanation of how the device works, and what children will learn from using it.

Final Report Requirements

The final report serves two purposes: it summarizes the work accomplished by the student team, and it provides them with an opportunity to reflect on the design, teamwork and presentation experience. The deliverables identified above are to be included in the final report, along with a reflective section describing the team’s experiences working as a team, how it might have been improved (if applicable), what they have learned during the course of the project, and what they might have done differently with respect to the device itself.

Peer Evaluations

Teaching students how to form and contribute to effective teams is an ongoing challenge in engineering education. Project teams formed in their courses are always somewhat artificial and lack the leadership hierarchy that would already exist in a professional setting. Teams created by arbitrarily grouping students often include members with lower levels of engagement and enthusiasm who know that other students will simply work harder to achieve the outcomes they desire. The design projects in this course include a peer assessment mechanism that is specifically designed to discourage these “opportunist/parasite” behaviors [5]. In order to exemplify the pressures and restrictions that exist in all real team situations, the student projects must include a system with similar rewards and consequences for the behavior of the team members. Specifically, the students must understand that they will succeed or fail together, although individual effort is recognized and rewarded. Over a number of offerings of this course we have developed and refined a grading system that attempts to reveal these concepts.

During this course students participate in four design teams, one in each seminar and another for the final design project, and they are required to provide peer evaluations at the end of each experience. These evaluations are confidential and ask each team member to evaluate their own contribution to the team as well as that of the other members. The objectivity of teenagers in their first semester of college can be diminished by a number of factors [6] so the faculty advisor in each seminar reviews the evaluations for objectivity, fairness and consistency. Based on the collected evaluations within a team, individual team members may be rewarded or penalized when determining their final grade for the seminar. After the first seminar it is not uncommon for all of the students to attach little significance to the peer evaluation and simply indicate that the level of effort and participation was equal for all team members. In that case the peer evaluations will have no effect on the grade received by each team member. However, they learn quickly that there are high expectations for the team projects and that the cost of failing to meet project requirements is significant. Furthermore, failing to complete the peer evaluation process carries a large penalty.

At the conclusion of the second seminar the students will tend to be more reflective and expressive about the relative contributions of the other team members with respect to their own. At this time they discover that the negative impact of a poor peer evaluation is much more significant than the reward given to those who make disproportionally large contributions, as shown in Figure 1. The maximum grade adjustment is 40 points (of 100 possible points) but points are lost much more easily than they are gained. The peer grading system discourages assertive individuals from seizing control of a project team, and provides a strong incentive for all team members to contribute to the success of the team as a whole. Cooperation within the team becomes necessary for any member to be highly successful.

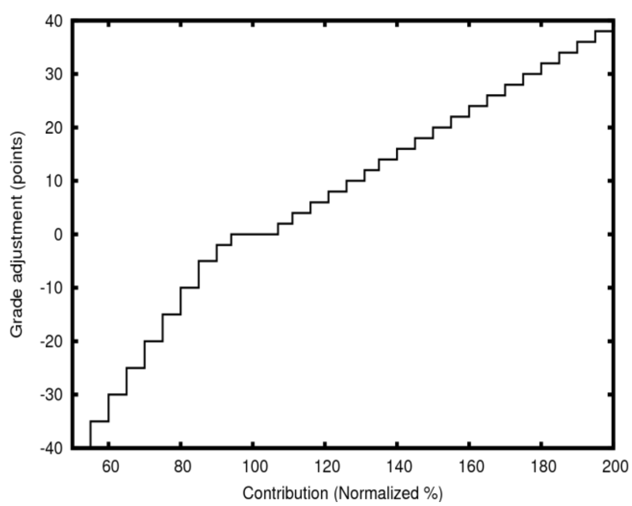

FIGURE 1
GRADE ADJUSTMENTS FROM PEER EVALUATIONS

CONCLUDING REMARKS

The design/build project described herein serves as an effective culminating engineering design experience in the introductory engineering course. Spanning just three weeks of the semester, it enables the balance of the course to provide both breadth and depth experiences in engineering as a profession and its disciplines while building towards this final comprehensive project. The project has been carefully developed so as to avoid requiring students to use technical skills or software that is beyond their educational experience. Instead, the project serves as a mechanism to execute the engineering design process with significant project constraints, work in teams with assigned peers, interact with and be responsive to both primary and secondary customers, and fabricate a working prototype that must withstand the enthusiastic exploration of 10-year-old children.

The project is undertaken by 50 student teams guided by five faculty advisers and multiple customers from outside the course. Achieving consistency in expectations, educational experiences and outcomes with such a structure and limited time requires careful preparation, cooperation, and communication on the part of the faculty and customers and presents multiple opportunities for organizational deficiencies to negatively impact the students' experience in the project. Nevertheless, the project is considered a successful and important culminating educational experience in the course by both faculty and students. While the students view the project as particularly challenging on multiple fronts, it is also one of the most positively-assessed elements of the course. In the most recent offering of the course, end-of-semester course evaluation responses to the statement: *"The course project was a valuable component of the course"* resulted in an average evaluation rating of 4.35 on a 1 to 5 scale, with 4 being "agree" and 5 being "strongly agree."

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