I&E PRINCIPLES AS A CONTEXT FOR ENGINEERING PROFESSIONAL SKILLS DEVELOPMENT

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Abstract

One approach to a first-year engineering course for students from a variety of disciplines is to target the course at developing skills and principles that transcend the fields—recognizing engineering as a general subject area instead of focusing on a sampling of narrow topics from each discipline. Hallmarks of engineering as a field of study include the application of problem solving and design processes based on observation and modeling of behavior grounded in knowledge of scientific principles to address societal needs. As a context for practicing and developing these and other professional competencies, a product-based innovation project incorporating tools and techniques from the areas of engineering design and innovation and entrepreneurship (I & E) was developed. Details on the motivation for and means of integrating I&E principles (through exercises related to idea generation, customer understanding, and an innovation canvas) into an introductory engineering course are presented.

Introduction and Background

This paper details the implementation of a product-based innovation project that incorporates tools and techniques from the areas of engineering design as well as innovation and entrepreneurship (I & E). The project serves as a culminating course activity for first-year engineering students among the Civil Engineering (CE), Construction Management (CM), Mechanical Engineering (ME), and Electrical and Computer Engineering (ECE) disciplines at Norwich University. The mission of the Norwich University College of Professional Schools is "to provide our students with the means, motivation, confidence and empathy to engage the problems of our era and create the industries, systems, processes, machines and structures that are required of our evolving society (Norwich University, College n.d.)." Within the college, Norwich's David Crawford School of Engineering emphasizes hands-on learning aimed at solving real-world problems in the spirit of that mission and the innovative, founding principles of the institution—to create an education system that would "…make efficient and useful citizens" (Norwich University, History n.d.).

All students from an engineering discipline at Norwich University complete a general introduction to engineering course in the fall semester that familiarizes them with various fundamental skills and tools of the engineering profession. The concepts introduced include the technical and non-technical aspects of engineering problem-solving and design, graphical communication skills, data collection, modeling, and analysis. By concluding the course with a product innovation-focused activity, an opportunity exists to thrust the students into a project with a meaningful, relatable context along with realistic non-technical constraints and parameters early on in their academic careers. A project of this description can support the development of the participants' professional skills, ABET-related and otherwise, and inspire student motivation and innovation.

Previously, this project was undertaken in the course for the aforementioned objectives and was implemented using classical systems engineering and business plan development techniques. Recently, the project implementation was modified to include more active, human-centered techniques and tools from the innovation and entrepreneurship (I & E) domain. The remainder of this introductory section will provide background information on the ABET student outcomes, the objectives of the freshman-level introductory course, and motivation theory. Following the introductory section, project implementation details that include the integration and application of exercises related to idea generation, customer understanding, down-selection, and an innovation canvas will be presented.

ABET Student Outcomes

A list of the Criterion 3 student outcomes from the ABET Engineering Accreditation Commission is excerpted below (EAC 2014):

> Criterion 3. Student Outcomes
>
> The program must have documented student outcomes that prepare graduates to attain the program educational objectives.
>
> Student outcomes are outcomes (a) through (k) plus any additional outcomes that may be articulated by the program.
>
> (a) an ability to apply knowledge of mathematics, science, and engineering
>
> (b) an ability to design and conduct experiments, as well as to analyze and interpret data
>
> (c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
>
> (d) an ability to function on multidisciplinary teams
>
> (e) an ability to identify, formulate, and solve engineering problems
>
> (f) an understanding of professional and ethical responsibility
>
> (g) an ability to communicate effectively
>
> (h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
>
> (i) a recognition of the need for, and an ability to engage in life-long learning
>
> (j) a knowledge of contemporary issues
>
> (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Programs seeking accreditation must develop and publish broad program goals and specific outcomes that encompass at a minimum the student-centered outcomes listed above.

Some of the skills programs aspire to develop in their students stem from a general or broad education fundamental to many programs, while others are derived from specific, specialized education or instruction related to academic discipline. Additionally, some of the traits are born out of a general skill with people that is often not specifically taught, but is hopefully tangential to education and experience, while others are best suited for development at the confluence of multiple contexts or bases of instruction. Once such interpretation or mapping of the outcomes is presented below in Figure 1.

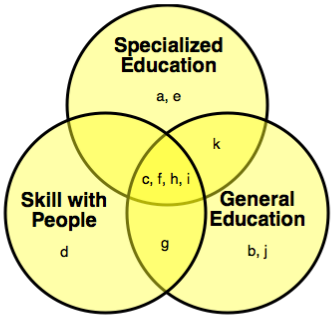

Figure 1. A Venn diagram mapping the ABET criterion 3 student outcomes (a-k) to the contexts or instruction bases from which they stem.

The mapping presented in Figure 1 is not meant to be definitive, rather it is presented to illustrate that the student outcomes desired are best developed from multiple contexts and perspectives. It is also current practice to map the outcomes to the objectives of many individual courses.

Course Objectives

Building on the above mentioned student outcomes, a team of Norwich faculty members related a number of the outcomes to specific objectives for the introductory engineering course when developing the overall curricula for their engineering programs. The course objectives and their relationship to the various ABET student outcomes are provided below.

This course intends to offer instruction and provide students experience with each of the following outcomes:

- an ability to describe the various engineering disciplines and typical roles of engineers within those disciplines
- an ability to acquire, analyze, and present data of experimental analysis (b)
- an ability to systematically design a process or system to meet desired needs within realistic constraints while applying project planning and management techniques (c)
- an ability to function on multidisciplinary teams (d)
- an ability to communicate effectively through oral, written, and visual means (g)
- an ability to recognize non-technical considerations during the design process and to understand the impact of engineering solutions in global, economic, environmental, and societal contexts (h)
- a recognition of the responsibility of engineers in regard to the well-being and safety of others and an embracing of the need to engage in life-long learning (i)
- a knowledge of contemporary issues faced by engineers in the workplace (j)
- an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice, including: basic programming fundamentals, computer-aided drafting and modeling, and statistics (k)
- an ability to demonstrate initiative and perform in leadership roles (l)

Note that outcome (l) listed above is a statement of a locally adopted student outcome related to leadership that was added and is required by the author's institution for all engineering programs.

Motivation Theory

Deci's theory on motivation tells us that one can actively construct experiences in ways that increase the intrinsic motivation of others. This is best accomplished by designing the experiences to create a sense of autonomy ***(direct one's own life)***, relatedness ***(connection to a community or something larger than one's self),*** and competency ***(progress towards mastery of a skill)*** among its participants (Deci and Flaste 1995). Daniel Pink popularized Deci's theory and examined it through the lens of a modern worker in a creative/information economy. He summarized the three elements key to motivating a worker as autonomy, purpose, and mastery (Pink 2011). Mastery experiences have been noted as key to shaping many students' self-efficacy beliefs; a student's self-perception of content mastery is highly linked to their self-reported enjoyment, interest, and satisfaction (Hutchison et al. 2006).

This theory suggests that course activities that are specifically designed to allow for student autonomy, connect to a larger societal context or purpose, and are scaffolded to provide opportunities for students to build on skills and competencies previously developed, can be powerful at improving a student's motivation for learning.

Project Implementation Details

Building on the background information previously presented, a culminating activity for a freshman-level introductory engineering course was developed. In developing the course module, it was desirable that the activity support improved student motivation for learning and engagement by creating opportunities for autonomy, relatedness, and competency development. Additionally, the project needed to build on key skills and processes fundamental to most engineering disciplines that were previously introduced and practiced in the course—engineering graphics, visual communication, engineering design processes, down-selection, teaming, and data analysis. Lastly, the project needed to provide a rich context for students to exercise and develop skills related to eight of the eleven ABET student outcomes, as well as a number of course-specific objectives. A description of the project components, along with the rationale for their inclusion, will follow throughout the remainder of this section.

The student prompt describing the project is reproduced below. A high-level outline of the project timeline and associated deliverables is provided in Appendix A.

> Your team has been promoted—you are now a design group for a local consumer products company. In this capacity, you are asked to conceive a marketable product that addresses a specific problem or challenge for a target customer. Through this process, you will ***define a value proposition, innovate a novel product concept, identify target customer segments, and enumerate key resources required to turn your innovative concept into an invention***.
>
> Each group will present their work to their lab section; the presentation must:
>
> 1. highlight your product concept,
> 2. visually depict the product,
> 3. define the value proposition,
> 4. define the customer segments,
> 5. connect the design to customer needs,
> 6. and convey the requisite skills and resources needed to see the design concept through to fruition.
>
> As your product design develops throughout the course of the exercise, it is important to remember that engineers must always be aware of real world factors and be able to adapt to the limitations imposed by "reality."

Using the prompt as a guide for exploring the project implementation, it is important to start by noting that the technical scope of the project is quite limited. In a course designed for first semester, first-year students, little can be assumed about their previous academic experiences and preparation. As such, the technical scope of the project was constrained such that first-year students with little experience would have a high probability of succeeding at the endeavor. This resulted in a relatively low performance expectations—simply that their design process result in a product concept and depiction (items 1 and 2). Constructing and constraining the project in this manner is critical to the perception of the project as a "mastery experience" by most of the participants. Despite this low technical performance expectation, the project builds competency by reinforcing skills and concepts previously introduced in the course related to engineering drawing and graphical communication (item 2), and the application of systematic processes for evaluation and selection through the use of decision matrices. Additionally, the project allows for a sense of autonomy, as the teams of students are free to select the problem area and focus of their endeavor. Directed brainstorming exercises were combined with carefully tuned criteria for use in the down-selection process to help students select one specific problem or problem focus area. Those same tools were used to build relatedness or purpose—focusing the students' thinking to problems of real human import. An example decision matrix used in this process is provided in Appendix B. In these aspects, the project was designed to improve the students' motivation for engaging with and excelling in their completion of the project.

The most critical element of the project is the traceability of the product design. Students are introduced to human-centered design concepts that are best summarized through the Venn diagram in figure 2. Throughout the design process, students are tasked with validating their understanding of the problem to be solved by interacting with and interviewing stakeholders and prospective customers about their pains and needs without providing any details on their solution. Throughout the evolution of their product concept and in the final presentation, the students must demonstrate that key components of their concept and solution flow logically from what was learned through the customer interview process (item 5). Students are also tasked with exploring and identifying the technical skill sets and areas of expertise that would be necessary to see their product concepts through to fruition (item 6). This exercise is designed to have the students explore their respective fields of study and opportunities for future coursework, connecting what they will or could study to a problem with real world context—hopefully seeding meaningful future pursuits. Lastly, throughout the activity students are required to schedule the time and resources necessary to produce the required deliverables through the use of a Gantt chart project management tool, providing traceability between the team's effort and project outputs.

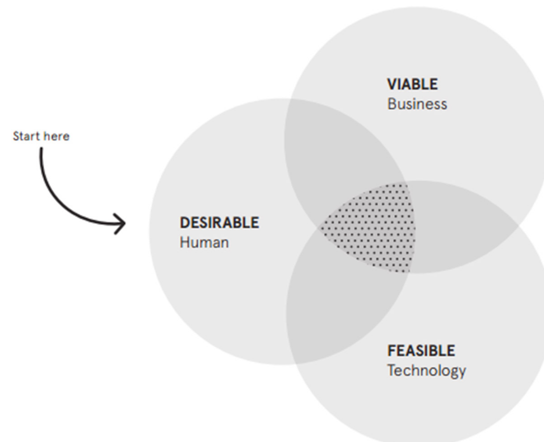

Figure 2. IDEO's human-centered design paradigm, emphasizing that successful solutions stem from where the possible set of appealing and desirable solutions intersects those that are technically possible and affordable (IDEO 2015, 14).

Human-centered design techniques that involve the gathering of primary research data through customer canvassing combined with the use of classical engineering design and project management tools (decision matrices, Gantt charts) were used to connect the students and their design process to a potential customer base, to a real-world problem, and to their future academic pursuits. To assist the students as they worked to develop a better understanding of a problem and devise a product-based solution or intervention, the "innovation canvas" developed at Rose-Hulman was employed. The innovation canvas (http://www.rose-hulman.edu/offices-and-services/office-of-innovation-engagement/innovation-canvas.aspx) is a design tool that incorporates technical and business or market factors by integrating classical engineering and product design processes with key elements of the business opportunity canvas developed by Osterwalder and Pigneur and detailed in the text *Business Model Generation* (Kline et al. 2013). The business canvas tool focuses on developing new business models and innovating new ways to create, deliver, and capture value in a business or enterprise. The innovation canvas uses the concept of value proposition development to inform students as they work to construct a solution identifying the minimally essential set of elements or offerings, defining the user/solution interactions, and identifying marketing and supply chain elements critical to implementation and success. Ahmed's 2014 paper details the use of the tool within various courses and provides an example canvas completed on a previously designed product (Ahmed, at al. 2014). Student teams use the innovation canvas in an iterative fashion to develop a value proposition (item 3), select the best first customer for their solution (item 4), and ideate and define a possible product in terms of the key benefits it must provide its user, the principle ways in which the user would interact with the solution, and the technical features or problems that must be addressed to provide the intended benefits.

Conclusions

The landscape of first-year introductory engineering courses includes many offerings that are designed to help students develop "soft" or non-technical professional skills while serving populations with diverse academic experience and little common foundation. Frequently, the students following these courses have high expectations for hands-on interactive experiences. Additionally, many students report that they do not consider paper-based or computer-based active exercises as "hands-on." This presents a challenge when designing exercises to address the expectations and needs of the various constituencies.

Considering the environment and employing human-centered design principles, this author decided to incorporate multiple current techniques from the realm of innovation and entrepreneurship education to address the above challenges. A product-focused innovation project for first-year students can be structured in such a way as to accommodate students from a broad range of previous academic experiences, and to create an environment supportive of increased student motivation. After four years of executing a product innovation-based project with first-year students at this university using various techniques, this author and the team of lab instructors for the course have observed that incorporating modern, customer-centric practices that emphasize firsthand gathering over classical research methods was successful at improving the significance and possible impact of the student-identified problems. Throughout this same observation period, all methods and iterations resulted in student work products that showed evidence that the students were applying the demonstrated techniques related to evaluating designs against constraints and the use of engineering drawings. One challenge that remains an issue is the resistance of the students to focus their design process on identifying key functional interactions and identifying the skill sets and technical areas where one would seek a solution. They seem dissatisfied with this step and tend to focus on designing solutions lacking in feasibility due to their grossly lacking technical competency. As a result, the challenge remains to design a context that is both realistic enough to connect students to the real-world and provide a platform for them to practice many professional skills, including outcomes c, d, g, h, i, and j, while remaining simple enough for them to design and implement a solution that is rooted in predictive modeling.

Lastly, the design project detailed is implemented across multiple "laboratory" sections with multiple instructors. One common observation that resonates from the instructors is that the students appear to understand the big picture concepts of the design process, but they struggle with planning their execution. Despite the introduction of multiple project planning techniques including traditional task dependency charts (PERT charts) and Gantt charts, the students need a lot of guidance in organizing and executing their projects. This challenge has persisted through all iterations and additional work is necessary to develop those skills prior to the project so the performance of the students can be more in line with what's appropriate for the project scope.

Future work on this project will involve refinement to the project management and problem definition phases; collection and analysis of data regarding student motivation; and collection and analysis of data related to student innovation self-efficacy beliefs using a tool such as the one developed by Gerber et al (2012).

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Appendix A: Project Outline

High-Level Project Timeline with Deliverables

- Pre-lab 1
  - Identify Problems to Solve/Needs
- Lab 1
  - Project planning – Role Assignments and Gantt Chart Discussion
  - Ideation (Problem)
    - Individual listing exercise
    - Sorting/Categorizing
    - Prophet-Scribe Model
  - Down-Selection (Use of Decision Matrix)
  - Milestone: Human Need or Problem Identified
  - Ideation (Solutions)
    - SCAMPER
    - Other techniques
- Post Lab 1
  - Customer Canvassing
  - Group meeting or discussion – problem and solution refinement
  - Milestone: Draft Value Proposition
  - Milestone: Initial Gantt Chart
- Lab 2
  - Deliverable: Initial Gantt Chart
  - Innovation Canvas
  - Value Proposition Evolution
  - Key Benefits/Needs Addressed
  - Functional Diagrams/ Define User Interactions
  - Address Non-Technical Concerns
  - Skills, Resources, and Technologies Needed to Solve
  - Deliverable: Draft Innovation Canvas
- Post Lab 2
  - Innovation Canvas and Product refinement
  - Presentation drafting
  - Presentation practice
- Lab 3
  - Elevator Pitch
  - Presentation
  - Presentation Review/De-brief
  - Deliverables:
    - Final Gantt Chart
    - Presentation Slides
    - Elevator Pitch Script or Outline
    - Peer Evaluations (In-Class)

Appendix B – Decision Matrix for Problem / Need Down-Selection

Table 1 - Example Decision Matrix

CRITERIA	WEIGHT	NEED 1	NEED 2	NEED 3	NEED 4
Simplicity (Easy to address?)	1				
Originality (Does team have unique insight?)	1				
Potential Benefit (Be useful!)	1				
Potential Impact (# People positively impacted?)	1				
Barriers (Regulatory? Safety? Competition?)	1				
Total					