AC 2012-3555: THE IMPACT OF A HYBRID INSTRUCTIONAL DESIGN IN A FIRST-YEAR DESIGN (CORNERSTONE) COURSE ON STUDENT UNDERSTANDING OF THE ENGINEERING DESIGN PROCESS

Prof. Susan K. Donohue, University of Virginia

Susan Donohue is a lecturer in the School of Engineering and Applied Science. She taught ENGR 1620, Introduction to Engineering, in fall 2011. Her research interests include K-20 engineering education with an emphasis on design, development of spatial skills, and identification and remediation of misconceptions.

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Abstract

Engineering is synonymous with design, and the interchangeable use of the terms is ubiquitous in society: see, for example, Quicken Loans' slogan "Engineered to Amaze."[30] Design classes are therefore fundamental to an undergraduate engineering plan of study; the gains in student performance and retention due to involvement in design activities are well documented in the literature. Design is also one of the criteria by which programs are evaluated for ABET accreditation.[6] Therefore, the issue is not "should we offer design courses"; the issues concern course structure and content. A hybrid instructional design for a cornerstone course is presented and its efficacy in promoting student understanding of the engineering design process investigated. The instructional design is called a "hybrid" because it uses both short-term and long-term projects to provide coverage that explores topics in both depth and breadth instead of just short-term or just long-term projects. A review of relevant artifacts from the Fall, 2011 semester indicates that the research goal was achieved.

Introduction

In first-year engineering undergraduate programs with a design component, students are typically introduced to the concept and practice of engineering design primarily through lecture, discussion, and project-based/design-build-test activities.[5, 13, 16, 20] A key instructional decision is to choose which pedagogy(ies) to emphasize; for the semester reported here, I chose to use project-based learning activities[27] emphasizing design-build-test and, to a smaller extent, discussion to maximize active learning opportunities. With project-based learning, a following decision is whether to stress depth or breadth of exposure to the topic, resulting in students being involved in one main project or a series of smaller projects, respectively; the choice depends on the amount of latitude the instructor has in designing the course syllabus and schedule and overall program goals and requirements. Both depth and breadth approaches have merits and drawbacks, leading to the question whether a hybrid instructional design – "hybrid" in the sense that students are provided with both depth and breadth learning experiences – can capitalize on the strengths of both approaches to provide students an optimal design education experience.

This paper will report the effectiveness of this instructional design in students internalizing and subsequently owning key concepts and practices of the engineering design process. The class is organized in two parts: a "design boot camp" in which students are involved in design challenges from the first day of class for the first half of the semester, and an in-depth challenge during the second half. The design boot camp is structured along the lines of the engineering design process; student teams iterate through the cycle of identifying a problem or need, developing of a set of solutions from which one is selected for prototyping, testing, evaluation, and reporting for three challenges of increasing complexity and constraints.

The research question, therefore, is whether a hybrid instructional design that uses a "boot camp" of increasingly more complex short-term projects introducing first-year students to key engineering design domains paired with an in-depth project on a topic shown to be successful in engaging students provides a learning experience that results in solid, comprehensive knowledge of the engineering design process. That is, will the following objective common to all sections of ENGR 1620, Introduction to Engineering, be achieved?

Objective #1:	**Introduce students to the real world of engineering and design**
Outcome #1:	Understand and apply the structured approach used by engineers to solve open-ended design problems[11]

Assessment and evaluation of student abilities to internalize and eventually "own" the engineering design process is done with a mixed methods approach. Improvement in defining problems and designing solutions is tracked through performance on appropriate sections of documentation deliverables and exam questions; qualitative evaluation of reflections on the challenge and process in student engineering notebooks is used to validate the quantitative measures and link knowledge about the engineering design process to participation in this course. Due to its structure and the amount and type of data, this investigation is preliminary and informal in nature. Tasks such as rigorous, systematic comparisons to outcomes from other course sections would be part of a more formal research design.

The paper is organized as follows: information on the course under study, ENGR 1620, is provided and the three main engineering design process models used in my sections are briefly described. The design challenges are explained in detail. Student performance on the tracked items listed above is described and analyzed, conclusions drawn, and directions for future work outlined.

ENGR 1620 Course Information

ENGR 1620 is a required course for first-year students in the University of Virginia's School of Engineering and Applied Science (UVa SEAS).[15] It is offered only in the fall and has a classroom (3 credits) and a lab (1 credit) component. There is a separate section for students in the Rodman Scholars Program, SEAS's honor program. The course is administered by the Associate Dean for Undergraduate Programs' Office. Professors are recruited from every engineering department in SEAS to lead the classroom sections. Another associate dean facilitates the lab sections, providing a common learning experience for the first-years. The professors of the classroom sections determine their sections' content and schedule. There are two common learning objectives for the course.[11, 24]

SEAS had 670 first-year students matriculate in Fall, 2011. There were 18 sections of the course with an average enrollment of 37 students in Fall, 2011; section enrollment ranged from a minimum of 26 to a maximum of 41.[32]

Table 1 provides a breakdown by gender and primary ethnicity for the students in Sections 13 and 18, the sections studied in this work. The University's Office for Institutional Assessment and Studies reports that females comprise 31% of the SEAS undergraduate population; the percentage of female students is 24% and 43%, respectively, for Sections 13 and 18.[25, 33, 34] The representativeness of student ethnicities in the sections with respect to SEAS is detailed in Table

2, following. The SEAS percentages in that table do not sum to 100% because not all categories for which data are collected are reported. Student demographic data by class years – e.g., by first year – are not available at this time.

This information is reported to provide a sense of the representativeness of the sections with respect to the SEAS undergraduate student body. A portion of the seats in all sections are reserved for each summer orientation session to allow students registering in August roughly the same opportunities as students registering in June. The numbers do not justify analysis with respect to ethnicity; analysis with respect to gender may be supported with an additional semester of data. However, it has been demonstrated that the projects which engage students from underrepresented populations in science, technology, engineering, and mathematics tend to engage majority students, while the reverse may not be true; see, for example, Cole and Espinoza[8]; Murphy, *et al.*[21]; and Whitten, *et al.*[35] Therefore, analysis with respect to gender and ethnicity may tend to validate that finding rather than demonstrate new effects.

Table 1. Student Demographics, ENGR 1620 Sections 13 and 18, Fall 2011[33, 34]

	Section 13		Section 18	
	Female	Male	Female	Male
African American	0	0	2	2
Asian American	2	7	2	3
Caucasian	6	18	11	16
Hispanic American	1	2	0	0
Foreign National	0	2	1	0
Category Totals	9	29	16	21
Section Totals	38		37	

Table 2. Representativeness of Section Enrollment by Ethnicity, Fall 2011[26, 33, 34]

	SEAS %	Section 13	Section 18
African American	5%	0%	11%
Asian American	16%	24%	14%
Caucasian	60%	63%	73%
Hispanic American	5%	8%	0%
Foreign National	5%	5%	3%

Engineering Design Process Models

Many models of the engineering design process exist; the three presented in Figures 1 – 3, below, are the main ones presented and discussed in the course. The first two were chosen based on several years experience in teaching design. The Massachusetts Department of Education's model is standards-based, designed for K-12 engineering education, and segments the process with sufficient granularity.[19] Reid Bailey's model emphasizes iteration and re-entry at multiple points; observations and anecdotal data confirm that the latter characteristic resonates with students. The third is from the course text.[14]

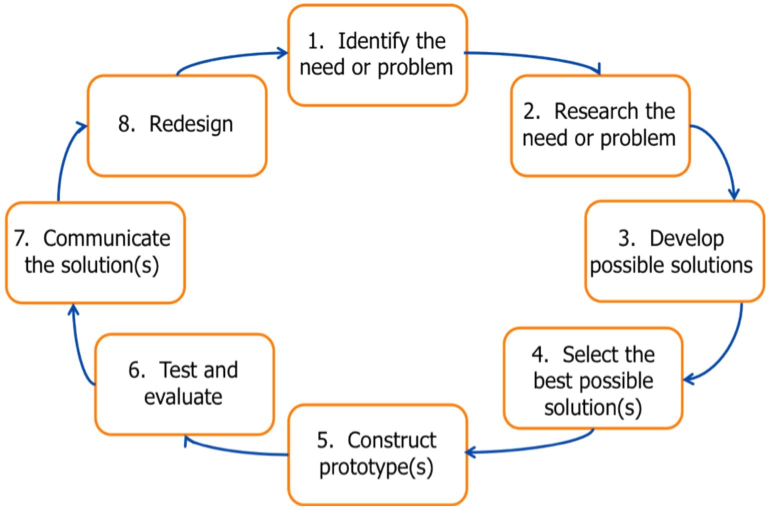

Figure 1. Massachusetts Department of Education (DoE) Engineering Design Process (p. 84)[19]

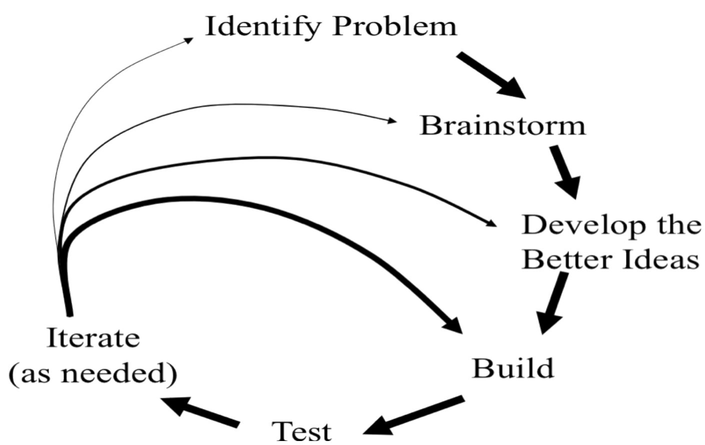

Figure 2. Reid Bailey's Engineering Design Process Model

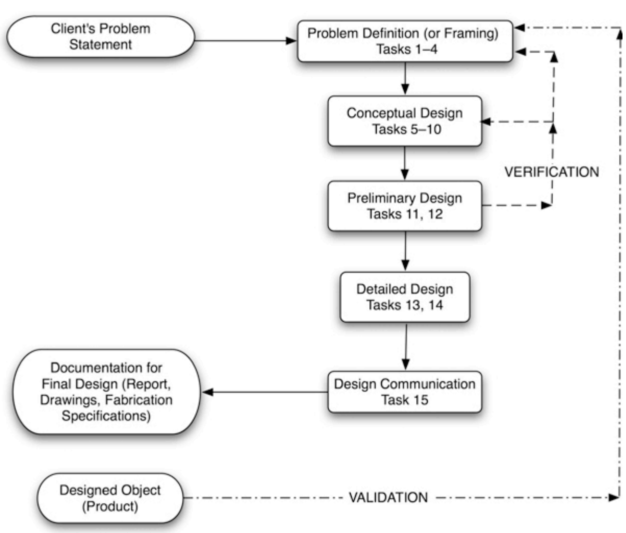

Figure 3. Dym and Little's Five Stage Prescriptive Model (p. 28)[14]

Design Challenges

The first three challenges comprise the "boot camp" portion of the course. The "boot camp" appellation comes from the demanding schedule and engagement from projects from the first day. In addition to learning about the engineering design process through participation in the project-based activities, students received specific exposure to the disciplines of civil and environmental, electrical, materials, mechanical, and systems engineering; several teams were also able to explore interests in chemical engineering. Biomedical and mechanical engineering are addressed in the AbilityOne challenge. This broad exposure is intentional. First year engineering students at UVa do not declare a major until their second semester, and another objective of the course is to give them sufficient experience with the various disciplines to help them make an informed decision about their major. The emphasis on environmental and service learning is intentional; research shows that these topics tend to have a superior ability to engage students in engineering studies.[9, 12, 18, 36]

Paper Towers (8.24 – 8.26; report due 8.31)

An impromptu exercise[7] about structures, Paper Towers, was the first project-based activity of the semester. It was scheduled for the first two class periods for several reasons: students would know and experience from the beginning how the course would be conducted in time to switch sections if a team project-based structure did not align with their interests, students who would switch in would not be at a disadvantage, and students would get to know their classmates more quickly. It is also a relatively simple, low-stress activity, allowing students to focus on the process as well as the structure.

The students formed teams by counting off. Each team received a small storage bin containing two pieces of 8.5" x 11" pieces of paper, one 8.5" x 11" piece of card stock, a 6" x 6" piece of corrugated cardboard, a ruler, a pair of scissors, and once settled in a work area, 18" of scotch tape. The challenge was to build the tallest structure that would stand alone, unsupported by any part of a student's body, with a golf ball at its apex, for one minute. Points were awarded based on height and ability to perform to expectations. Extra credit was given for the tower remaining upright when variable wind forces created by a Stanley Blower were directed at it from 18" away. While they were building and testing their towers, students also interviewed each other about their hometowns, fun or interesting facts about themselves, and their prior experiences with this activity. The personal background information and results were reported in a document submitted a week later, along with answers to the following questions:

- Describe the decisions you made during the design process
- What items and constraints did you have to take into consideration? How did your choices affect the final design?
- Did you do in-process testing? Why or why not?
- What, if anything, would you do differently if you had a chance to do this project again?

Plastic Bottle Repurposing Challenge (9.5 – 9.16; documentation due 9.9 and 9.16)
Alternative Energy Challenge (9.16 – 9.30; documentation due 9.23 and 9.30)

The next two design challenges, grounded in the National Academy of Engineering's Grand Challenges,[23] were purposefully chosen because of their relevancy and appeal to student interest in sustainability. Students learned about the ecological and economic disasters caused by the (improper) disposal of the virtually indestructible plastic bottle in the first, and the unsustainability and imminent exhaustion of fossil fuels in the second. The plastic bottle repurposing challenge had students finding a new use for discarded water bottles based on their choice of the National Academy of Engineering's Grand Challenges. The alternative energy challenge had students design cookers that did not use traditional organic or chemical fuel sources. Students also had to develop a model for predicting how long it would take to cook (as defined as melting shredded cheese to the point where the strands were indistinguishable) nachos with their method. Team membership was assigned by the instructor based on observations of strengths and weaknesses, with the main objective of having the students get to know each other better.

Students develop a proposed solution and then implement it within two weeks each for these challenges, with appropriate documentation due and presentations given at the end of each week. The proposal documentation is a subset of the product documentation, and is required to be rolled into the product documentation after incorporating faculty and student feedback.

AbilityOne Challenge (10.7 – 12.5; documentation due 10.28 and 12.6)

The "What's Next?" AbilityOne Challenge[17] is to develop an assistive technology device to support the employability of people with physical challenges. It is the in-depth challenge for the course. Self-selected student teams chose a physical challenge as part of problem identification and research activities. One student team won a seed money grant for supplies from the ASEE Design in Engineering Education Division, and will enter the College/University Competition in the near future.

Results

Student comprehension of the engineering design process is evaluated through analyses of grades on and content of documentation (team), exam questions (individual), and end-of-course reflection (individual). The latter two are accepted practices for the admittedly difficult process of assessing student learning in design classes.[4, 6, 27, 31] Analysis of proposal and project documentation is included even though the documents are a team product because they are artifacts of (corporate) student understanding of the design process. The traditional pre-assessment/intervention/post-assessment is followed in spirit; the midterm questions were not repeated in the final for pedagogic reasons.

Assessment of Team Learning

Interestingly, only a few students had previously performed the paper tower activity or a similar design activity, so it served as a good introduction to the course as well as a casual pre-assessment of student prior knowledge of the engineering design process. This activity is a fairly common one in classes that provide K-12 engineering education such as physics and technology education. The assumption, therefore, is that this course is the first exposure to the engineering design process for the majority of students.

Based on the grades for the questions listed above, almost all students were able to discuss well the decisions they made during the activity (average grade of 94%), but did not cover items and constraints nor their impact on the final design as well (average grade of 71%). They also described their in-process and adjustments well (average grade of 92%), making the connection between and transition from the scientific method, typically emphasized in high school, to the engineering design process. Students almost instinctively understood the iterative nature of the process.

Table 3 reports the average grades on key documentation sections for the plastic bottle, energy, and AbilityOne challenges. These sections are the ones common to both the proposal and project documentation. Students have the opportunity to revise these core sections for the project documentation based on instructor and peer feedback of the proposal documentation. The project documentation also has sections on design constraints and objectives, functional and non-functional requirements, and testing activities and results. The documentation format intentionally follows the engineering design process for reinforcement. The grades remain relatively consistent through all but the last documentation assignment, reflecting mastery struggles and changing team compositions. With respect to the former, teams were repeatedly observed trying to fit a problem to a solution rather than the reverse. Through mentoring, modeling, and repetition, only one team was solution-driven in its design activities at the end of the semester and several team members mentioned in their course reflections that their product development would have been easier and less time-consuming if they had used a problem-driven approach.

Table 3. Average Grades on Key Documentation Sections

Challenge	Problem Statement	Problem Research	Solution Development and Selection
Plastic Bottle Repurposing			
Proposal	91%	91%	89%
Project	88%	90%	92%
Energy			
Proposal	89%	87%	89%
Project	89%	86%	92%
AbilityOne			
Proposal	88%	88%	88%
Project	96%	96%	95%

Assessment of Individual Learning

Midterm (10.14)

Student understanding of the engineering design process is assessed by four questions (please see the Appendix for question content) in the midterm. The results are summarized in Table 4. Average student performance is the worst on the first question, an analysis of a vignette with respect to the engineering design process. 26 of 75 students (35%) didn't address the process in its entirety in their analyses. The vignette is based on Bailey and Szabo[3] and Bailey, Szabo, and Sabers.[4] Table 5 reports most commonly made omissions and mistakes in the analyses obtained through a qualitative review of the responses. Codes are based on the expectation was that students would recognize that the vignette represents a solution-driven process, not a problem driven one, and that result does not represent the problem-driven approach taught in the class. The counts for the individual code categories don't add to 26 because a student's answer could contain both a mistake (or two or three) and omission. The code list is emergent: that is, themes and categories were developed over the course of scoring the documents.

Table 4. Average Scores on Questions Testing Knowledge of the Engineering Design Process (EDP)

	Average Scores on Design Questions		
Midterm	Section 13	Section 18	Overall
Engineering Design Process (15)	82%	89%	85%
The Role of Failure in Engineering (25)	92%	91%	91%
Solution Development and Selection (10)	88%	90%	89%
Nature of the Design Process (10)	93%	89%	91%
Final			
Important Process Steps (30)	94%	97%	95%

Table 5. Summary of Errors and Omissions in Student Vignette Analyses (Midterm)

Didn't mention problem identification and research at all	15
Student stated that s/he needed more information to comment	14
Assumed client had addressed problem identification and research	10
Prototype/develop solution as presented	
without optimization	5
with optimization	5

Final (12.9)

By the final, only 6 students now give answers that are more solution driven than problem driven and/or do not demonstrate a firm grasp of the engineering design process. Students were asked to identify the process model that best fit their work and identify the four steps they felt most important in the process. Table 6 presents the results for the two most popular models, the Massachusetts Department of Education (DoE) model[18] and Reid Bailey's (UVa) model; see Figures 1 and 2, above. Eight students chose the model presented in Dym and Little[14]; there, too, problem solving, solution development, testing, and revising/optimization were identified as the most important steps. One student chose to comment on Boston's Museum of Science Ask, Imagine, Plan, Create, and Improve model.[22] An analysis of the reasons for selection reveals a generally solid understanding of the process steps. The average grade for the question is 95%, as documented in Table 4, above.

Table 6. Important Steps in the Engineering Design Process as Identified by Students (Final)

	Percent Chosen by Students		
Massachusetts DoE Model	Section 13	Section 18	Overall
Identify the Need or Problem	95%	71%	82%
Research the Need or Problem	24%	25%	24%
Develop Possible Solutions	67%	88%	78%
Select the Best Possible Solution(s)	19%	13%	16%
Construct a Prototype	52%	50%	51%
Test and Evaluate	86%	67%	76%
Communicate the Solution(s)	24%	42%	33%
Redesign	38%	38%	38%
Reid Bailey's Model (UVa)	Section 13	Section 18	Overall
Identify the Problem	82%	70%	76%
Brainstorm	64%	80%	71%
Develop Better Ideas	27%	30%	29%
Build	73%	70%	71%
Test	82%	90%	86%
Iterate	73%	50%	62%

But Is Their Learning Necessarily Linked to This Course and Design?

A qualitative review of student end-of-course reflections on the engineering design process was performed to determine whether their knowledge can be attributed to this course and its specific structure. An analysis of coded responses, the most popular of which are listed in Table 7, supports the conclusion that knowledge about the engineering design process is connected to this course and its design. Several students also reported that even though the course was "a lot of work – the paperwork was time consuming" the opportunity to work through four challenges provided the repetition necessary for mastery learning. In their words:

> It feels like this is how engineering is, not sugar coated; (it was) taught the best way: by experience; many projects made me…more of an engineer; I have much more confidence in my ability to be an engineer now than I did at the beginning of the semester; I learned how important it is to start by identifying a problem first and then looking for solutions; the repetition engrained the process in my brain – now it's second nature; the projects helped reinforce the book definitions; I thought documentation was an annoyance but now I see its worth; no pressure meant we could really get a feel for the process – we were not punished for failure; (b)efore this course I hadn't thought nearly as creatively or in such a problem solving way so I am very grateful for this course.

This conclusion was validated by class discussion in both sections.

As with the qualitative review of the vignette analyses, a student's answer could contain more than one code response. This code list is emergent as well.

Table 7. Student Responses Linking Knowledge and Course

Learned about the design process from this course	15
Course structure helped focus my learning	8
Project-based approach is the best for learning engineering	7
I learned to define the problem first and then develop (a) solution(s)	6
I learned about team/time management from this course	6
Process is "second nature" for me now	4

In addition to asking whether the reported results are linked to the course's hybrid instructional design, it is worth asking whether the results can be linked solely to this design. I did not use one section as a control for pedagogic reasons. Other course sections using different instructional designs and instructors can serve as weak controls in retrospect; however, many sections did not track the same outcomes as reported in this work. One instructor who used assessments based on Bailey and Szabo[3] and Bailey, Szabo, and Sabers[4] reported a large increase in understanding of the importance of problem definition after a qualitative review of student answers: up to roughly 70% of his students recognized that the engineering design process is problem-driven by the end of the semester. The instructor has his students work in teams on one project during the semester, with students receiving in-depth immersion in a succession of stages of the engineering design process. He also used process and product documentation to reinforce learning. The main takeaway is that repetition reinforced learning in both instances.

Conclusions

I believe that the hybrid instructional design was successful in meaningful student learning because I was very transparent in my motivation and reasons with the students, and chose appropriate projects. I linked what they were doing, especially with respect to the documentation and presentations, to employer expectations. I described how the knowledge, skills, and abilities transferred to future courses in various majors. Students had reinforcement in design process activities through the development of proposal and project documentation. They also acquired ownership of their projects through their choice of physical design objects. Solutions were constrained only by problem area, materials, and budget. Creativity was encouraged.

A project-based pedagogy is *de rigueur* for a design course, regardless of the domain. The type and number of projects distinguish approaches and outcomes. The research question – whether a hybrid instructional design of a "boot camp" of increasingly more complex projects paired with an in-depth project on topics shown to be successful in engaging undergraduate engineering students provides a learning experience that results in student knowledge of the engineering design process – is answered in the affirmative for the short term. Whether this instructional design is successful in student long-term retention of design knowledge remains to be seen. Depending on the major and participation in extracurricular activities, students at my institution may not have another design course until their fourth year capstone. I have observed that a number of capstone students need remedial instruction in the engineering design process due to the passage of time without reinforcement and/or marginal understanding of the process. Creating an effective instructional design for a cornerstone course that results in long term design knowledge, skills, and abilities is the motivation for this research. The immediate goal of meeting the common course objective has been met, and a basis for future research developed. Future work, including systematic comparisons of outcomes with other course sections; the development of a validated pre-/post-assessment instrument; the use of a control group to evaluate whether the depth, breadth, or both approaches makes a difference in student outcomes; and a longitudinal study to determine knowledge retention throughout students' undergraduate careers will fully determine the worth of a hybrid instructional design in first-year cornerstone design courses.

Acknowledgments

I am grateful to Reid Bailey for sharing his experiences in and research on engineering design and the assessment thereof, to Larry G. Richards for years of sharing and mentorship, and to Edward Berger for giving me the opportunity to teach ENGR 1620. I thank the reviewers for their comments and suggestions. I am grateful to my students for their hard work and perseverance in ENGR 1620.

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Appendix

Engineering Design Process (midterm) (based on Bailey, *et al*.[3, 4])

You are a general consulting engineer. A prospective client comes into your office asking for help in building a prototype of the device he's sketched out in the margins of today's paper. You ask to make a copy of the sketch – after he's signed and dated it – so that you can evaluate the situation and possibly draw up a project schedule and cost estimate if you think the project is a good fit with your skill set. Evaluate this scenario with respect to the engineering design process. (15 points)

The Role of Failure in Design (inspired by Petroski[28])

The walkways over the atrium in the Kansas Hyatt Regency Hotel collapsed on 17 July 1981. Read these accounts,[1, 10] along with the discussion on pp. 13 – 15 in Dym and Little[14], and describe, in **detail**, three reasons for the walkways' collapse. (25 points)

Solution Development

Many areas of the world have either unreliable or no electricity service, resulting in 1.6 billion people living without electricity and 2.4 billion reliant on biological fuel sources.[2] Many people must rely on fuel-based illumination if they wish to work between sunset and sunrise, or to augment the sun's light when it is compromised (e.g., during a rain storm). However, there are drawbacks to using these fuel sources such as cost, availability, safety, and emission of unhealthy gases. Your overall goal is to identify an alternative, sustainable, and feasible method of illumination that does not have these drawbacks. Complete the following tasks to help you accomplish your goal.

Describe how you would develop a set of solutions to this problem and then select one to prototype. (10 points)

Thoughts on the Nature of the Design Process

Re-read the foreword in Dym and Little.[14] How much, in your opinion, is the design process art and how much science? Why? Provide at least four reasons in making your case. (10 points)

Engineering Design Process (final)

The engineering design process is the model for structuring our class projects (and documentation!). Refer to the process models in the notes for 9.2.11. Identify four steps that have the most importance or meaning to you in the process model that most closely reflects the one you followed and discuss why the steps are important to you. Give three reasons or examples for each step. Name the process model. (2 points for the process model, 1 point per step and 2 points per reason for 30 points total)