

AC 2010-2021: A STUDENT PERSPECTIVE ON FRESHMAN ENGINEERING DESIGN PROJECTS: DEVELOPING CORE SKILLS IN YOUNG ENGINEERS

Michael Pacella, University of Maryland, Baltimore County

Michael Pacella will graduate Summa Cum Laude in May 2010 with a BS degree in Chemical Engineering [Bioengineering track] from the University of Maryland, Baltimore County. He currently is a finalist for the 2010 UMBC Valedictorian. Michael has spent the last two years serving as a Teaching Fellow for the Introduction to Engineering Design Course at UMBC. In addition, he has been doing undergraduate research on developing and testing a kinetic model of *Chlamydomonas Reinhardtii* (a species of single-celled green algae) metabolism with the goal of optimizing lipid synthesis for biodiesel production. He will be attending graduate school at the Johns Hopkins University in Biomedical Engineering.

Taryn Bayles, University of Maryland, Baltimore County

Taryn Bayles is a Professor of the Practice of Chemical Engineering in the Chemical and Biochemical Engineering Department at UMBC, where she incorporates her industrial experience by bringing practical examples and interactive learning to help students understand fundamental engineering principles. Her current research focuses on engineering education, outreach and curriculum development.

A Student Perspective on Freshman Engineering Design Projects: Developing Core Skills in Young Engineers

Abstract:

As both a student and teaching fellow in an Introductory Engineering Design class, experiences and observations have allowed me to see the many benefits of the course's design project requirement. For many young engineers who chose their major based on an interest in math and science, the design project provides their first encounter with synthesis and evaluation, two skills that distinguish the engineering profession from the natural sciences. The design project requires that students utilize their knowledge and comprehension of math and science to inexpensively and efficiently build something to accomplish a set objective given a series of problem constraints. The design project also requires students to evaluate and reflect on not only their own work, but the work of their colleagues in the class as well. The skills of synthesis and evaluation later become crucial as students progress through their years as upperclassmen and enter the research or industrial fields. My own experience in undergraduate research and advanced engineering courses, particularly the senior design course, has clearly demonstrated this.

The design project also fosters the development of communication skills in young engineers. By working in diverse design groups of 4-6 students as part of a discussion section of ~30 students, young engineers gain experience in collaboration (both within and between groups) to determine the overall design scheme of the project as well as the creation and delegation of smaller individual tasks. Finally, the design project introduces young engineers to the theoretical and mathematical aspects of engineering design. Students are required to develop a mathematical model to predict the performance of their design based on their understanding of the governing scientific principles involved.

This paper will feature my perspective, both as a student and as a teaching fellow, of the Introduction to Engineering Design course and will provide detailed descriptions of the three design projects (and their potential solutions) which I have been involved with. In addition comparisons will be made using student assessments of course outcomes for each of the three years of the comparison (from both the student and faculty perspective).

Background

Curriculum:

The University of Maryland, Baltimore County (UMBC) has made alterations to its Introduction to Engineering Design (ENES 101) course, modifying it from a purely lecture and design-on-paper course to a more active learning and hands-on experience for the past ten years. As a senior chemical engineering major (bioengineering track) at UMBC who has worked as a teaching fellow for the ENES 101 course the past two years, I have both personally experienced the benefits of this alteration as a student and I have witnessed the impact these changes have had on other students as a teaching fellow. Implementation of this change has occurred over the past ten years via modifications and additions to the course curriculum. While the course still offers two fifty-minute sessions

of traditional lecture on principles of engineering science (dimensional analysis, data analysis, statics, mechanics of materials, heat transfer, and computational tools) and a two-hour discussion session; a hands-on team-oriented project based learning design project was added in an attempt to improve the overall effectiveness of the course by allowing students to become truly involved in their learning.

Discussion Session:

The two hour discussion session is organized by partitioning a class of roughly 200 students into smaller groups of 30, each of which meets once a week for a two hour session moderated by a teaching fellow: an upperclassmen engineering major who provides students with assistance in both their comprehension of course material and their adjustment to the university experience. In the early phases of the semester the two-hour discussion session, which meets in a computer lab, provides students with hands-on experience in the use of computational tools (Microsoft Word and Excel, AutoCAD, and MATLAB) to solve engineering problems. However, in the second half of the semester, once students have been assigned their design project, the discussion section provides a meeting time for the student's design groups, which consist of four to six students and are formed within each discussion section. Also during the latter portions of the semester, each teaching fellow's responsibilities shift somewhat from answering software and homework questions to providing assistance to groups in the design and construction of their design projects. It is through these interactions with groups over the past two years that I have gained insight into the efficacy of these newly introduced design projects.

Course Goals:

The addition of the project based learning design projects has also allowed the course to fulfill additional goals of the Chemical & Biochemical Engineering department's ABET objectives and outcomes, known as the "5 C's." According to the "5 C's," students should demonstrate, upon graduation, Competency in the discipline of chemical engineering, Critical thinking ability to solve complex problems, the ability to work in Cooperation with teammates, effective Communication skills, and Capacity for life-long learning. At the beginning of each semester a course objectives worksheet is provided to each student which indicates the ABET criteria which will be covered over the course of the semester. Although it is unlikely that a single freshman engineering course can prepare students to satisfy ABET criteria, it is a useful tool to gauge students' progress in their ability to utilize key engineering concepts and thought process. To this end, students are asked to provide a self assessment, via a survey of their progress in key ABET areas which were part of the course. Survey results from the three years of the course that is being discussed in this paper are provided in Table 1 (on the next page). This data is used to assess if there was a difference in the student's perception of the components of this course. While the course's previous curriculum addressed competency in the discipline, it lacked components that would allow students to critically design and analyze an open ended problem, to cooperate with one another and, in the process, learn effective communication skills. However, by introducing a design project that places students into groups of 4-6 that are both diverse in terms of academic accomplishment and engineering field or other major of interest, the new curriculum necessitates communication and cooperation. Because students in different fields of

engineering likely have different educational backgrounds and expertise, diverse groups necessitate communication in order to take full advantages of the cumulative knowledge of the group.

Table 1: Student Assessment of ABET Criteria; Competency, Critical Thinking Cooperation with Teammates, Communication and Capacity for Life-Long Learning.

Student Assessment of Course Outcomes			
	Fall 2006	Fall 2008	Fall 2009
	n = 182	n = 194	n = 186
Competency			
Ability to use math or science	3.78	3.89	3.96
Proficiency in engineering	3.09	2.94	4.03*
Ability to design process using engineering principles	3.23	3.21	4.02†
Ability to use the techniques, skills and modern engineering tools necessary for the practice of engineering	3.31	3.23	3.96‡
Critical Thinking			
Ability to analyze/solve open ended problems in engineering	3.19	3.10	3.89§
Ability to evaluate solutions or designs given constraints	3.87	3.94	4.09
Cooperation with Teammates			
Ability to work effectively in teams with others having different backgrounds	4.34	4.29	4.38
Ability to fill both leadership and supporting roles in a team	4.22	4.30	4.31
Communication			
Ability to communicate effectively in written form	3.90	4.05	4.06
Ability to communicate effectively in an oral form	3.96	4.07	4.03
Capacity for Life-Long Learning			
Ability to define problem given an open-ended questions or situation	3.95	3.89	4.11
Ability to locate tools and information relevant to a given problem	3.96	3.92	4.13
Ability to assimilate information relevant to a problem	3.95	3.95	4.09
Ability to assess your own ability/knowledge to solve a problem and determine when to seek help	4.08	4.16	4.11
Statistically significant differences: (p < 0.05): * p=1.33e-14; † p=4e-10; ‡ p=4.44e-9; § p=2.86e-9			
1 = Not at all; 5 = A great deal			

Design Projects Overview

Definition of Design Problem and Constraints:

Although the details of the ENES 101 design projects are changed significantly from year to year in order to promote creativity and original ideas, they typically display a few common similarities. Each design problem statement is very open ended, which encourages students to explore a variety of possibilities in their designs; however, physical and economic design constraints are imposed to insure that the construction and testing of each device is feasible. Additionally, requiring students to evaluate possible design solutions subject to constraints reinforces the engineering design process in students and provides an accurate simulation of the constrained design problems they will encounter both in their upper level classes and in the field. In addition to adhering to explicitly defined constraints, students are also encouraged, to some extent, to explore and create implicitly defined constraints based on their knowledge of what the final design's intended use is. An example of this would be considering what a typical biological vasculature flow rate might be when designing a heart lung machine or considering the realistic scale-up of a renewable energy harnessing system. Although the consideration of implicit constraints is encouraged, I believe students would benefit greatly if this aspect became a more integral portion of the design project. In many cases, I have observed that students merely take constraints for granted without considering why they may be necessary. The ability to create and evaluate constraints based on background knowledge of the problem at hand will become a crucial skill as students progress into their upper level engineering classes.

Design Construction:

Another feature shared by many of the design projects implemented in the last ten years is the construction of a tangible final design. Unlike many upper level engineering classes where designs are carried out purely on paper and never actually built due to their exceedingly complex nature, the ENES 101 design projects are typically kept simple (and small) enough to allow their actual final construction and evaluation. My observations indicate that this is a crucial aspect of the ENES 101 design projects. I clearly remember as a freshman engineer how much my interest in the project grew when my team actually began construction and testing. This is also a notion I have seen expressed by students a number of times as a teaching fellow. As freshmen, ENES 101 students lack the technical understanding to undertake highly complex problems and, as a result, seem to have little respect or interest in purely theoretical designs of larger and more elaborate systems. However, actually constructing and testing a design whose technical features are more familiar seems to give students a great sense of accomplishment. By starting with small scale designs based on familiar principles, students become prepared to take on larger scale theoretical designs (such as the design of an entire chemical plant) as upperclassmen and to eventually contribute to the design and actual construction of large scale projects in the industrial field.

Incorporation of Lecture Material:

A final commonality shared by many of the ENES 101 design projects is the integration of lecture principles into project design calculations. As part of each project,

groups must create a mathematical model based purely on engineering theory to predict the performance of their design prior to its implementation. In some cases, extra time is spent in lecture covering a specific principle relevant to that semester's design project. An example of this would be spending extra time to cover heat transfer in pipe flow for a heart lung machine project, or spending time covering buoyant and drag forces for a hot air balloon project. This feature of the course allows students to directly apply what they are learning in lecture to their own tangible design projects. In my experience as both a student and a teaching fellow I have observed this to be an invaluable feature of the course. I have found that many freshmen engineers have difficulty dealing purely with abstract mathematical concepts; for instance, a force balance between gravitational pull, buoyancy, and drag on a hot air balloon. However, when students encounter such forces firsthand by incorporating them into a mathematical model of a specific design their abstract mathematical understanding of them increases greatly.

Making Valid Engineering Assumptions:

Development of a mathematical model also introduces students to the concept of an engineering assumption. I have observed (and experienced) that very early in the stages of developing a mathematical model students begin to realize that they cannot possibly account for all of the phenomena occurring in a given design. This realization prompts students to make reasonable assumptions regarding their projects so that a predictive mathematical model can be created despite unaccounted variables and limitations in the students' technical knowledge of engineering and mathematics. This acquired ability to make reasonable engineering assumptions has helped me greatly, both in my undergraduate research and in my upper level engineering classes. Development of a student's first mathematical model signifies an important milestone in their academic career and will undoubtedly help them greatly as they progress into upper level engineering classes and begin using the tools of calculus to develop more and more sophisticated mathematical models of engineering problems.

Previous Design Projects: 2006

Design Problem and Constraints:

My first encounter with the newly implemented design projects was during my freshman year at UMBC, the fall of 2006. Our class was tasked with the design of a device to capture, store, and reuse energy, captured from a renewable source of wind, water, or solar energy. Each device was evaluated based on three criteria. The first of these criteria was the amount of energy the device was able to capture, store and convert, as evaluated by the length of time it was able to power a light bulb. The second criterion was the overall efficiency of the device, as measured by the useful work output divided by the total energy input. The final criterion was the overall cost of the device; a full description of this design project was previously presented ^(1, 2). I was the only chemical engineer in my group, which consisted of three other mechanical engineers and a computer engineer. All of the groups in my section used a rechargeable battery to store their captured energy; however, the method used by each group to capture this energy varied greatly. My group chose to capture solar energy using photoelectric cells;

additionally, we chose to distinguish ourselves from the other groups using solar power by installing a parabolic mirror to focus as much incident radiation as possible onto our cells, thus increasing the total energy we could capture without paying for additional photoelectric cells. Many other groups used various permutations of turbines to capture either wind or hydraulic power.

Observations and Impressions from a Student's Perspective:

At the time, as a freshman engineer I initially viewed this design project as simply another source of stress in my life; however, as our design evolved into the final product I became quite proud of our accomplishment. This design project represented the first time in my academic career I had truly used synthesis in a project; looking back on this project as a senior, I doubt I will ever forget this first milestone in my career as an engineer. This project also introduced me to the use of engineering calculations. As a major portion of our project report grade, and as a component of the final exam, we were required to complete rough calculations both to predict our device's performance and to calculate our device's overall efficiency. This was perhaps the first time in my academic career I was asked to complete such an open ended calculation requiring so many engineering assumptions and, although at the time it seemed quite stressful, looking back I believe it was an invaluable milestone in my academic career. This specific calculation would later become greatly helpful to me in my junior year thermodynamics course where my project group was asked to calculate efficiencies of both gasoline and hydrogen fuel-cell powered engines. Looking back, my freshman ENES 101 project was probably a major factor in thermodynamics becoming my favorite undergraduate course. As I remember it, our group communicated quite well despite our varied academic backgrounds and even came to work homework problems and study for course exams together because each group member developed communication skills. The communication skills I developed during this project have certainly become quite useful in my upper level courses where group based final projects are essentially a standard practice.

Previous Design Projects: 2008

Design Problem and Constraints:

My next experience with the ENES 101 design project was during my junior year when I began working as a teaching fellow for the honors section of ENES 101H. This year, the students were tasked with the design of a hot-air balloon capable of lifting a certain payload for a specified amount of time. Their projects were judged based on typical performance characteristics (the time aloft, payload, and cost) in addition to points assigned based on their ability to communicate with other design groups and points assigned based on the accuracy of a mathematical model they were required to develop to predict their balloon performance. These last criteria were implemented to further encourage the development of communication skills, not just within individual groups but also between groups (as is often the case for industrial designs), and to encourage the use of mathematics and engineering principles in the design process. Each group's ability to communicate with other groups was judged based on the clarity of the instructions they

created for the construction and testing of their balloon, which were passed on to separate “construction” and “testing” groups. The complete details of this design project has been previously described.^(3,4) Besides encouraging communication and cooperation between groups, this feature also encouraged the development of written communication skills to supplement the oral communication skills typically employed for intra-group communication.

Statistical Impact of Inter-Group Communication Component:

Since the implementation of the ENES 101 design project, which includes assigned design groups, students have consistently rated “cooperation with teammates” to be amongst the highest rated course outcomes on the end of semester survey, and according to data from 2008 (see Table 1) the addition of this communication skills component did not have a statistically significant impact on this rating. Nonetheless, I would argue that as long as the design project is sufficiently simple enough to allow easily constructed designs this additional communication component should be effective at fostering further inter-group communication, which will certainly become relevant to students planning to work for large industrial companies. As part of the formal design report, the students were required to provide construction / assembly instructions complete with a CAD drawing package. The average score on this section of the report was 63.2 % in previous semesters, and was 73.7 % during the fall 2008 semester (when assembly instructions were provided to the construction teams and also required in the formal report). A t-test conducted on the data sets showed that the increase in scores was statistically significant ($p < 0.05$; $p = 1.11e-2$). [Other outcomes related to the communication component of this project have been previously presented.⁽⁴⁾]

Observations and Impressions from a Mentor’s Perspective:

Much like I was as a freshman, I observed many of the groups in my discussion section to initially view the design project adversely; however, as the semester progressed I noticed more and more students beginning to enjoy working on their projects. One trend I have frequently observed in my discussion sections has been complaint coming from students who feel that some of the engineering principles taught in lecture do not apply to their specific field and, therefore, are a waste of time. Examples of this would be a chemical engineer complaining about doing truss analysis problems or a computer engineer complaining about having to use AutoCAD. However, when the students were working on their hot-air balloon design projects, which required the use of principles unspecific to any certain field, I observed that none of the students complained about the project being irrelevant to their major. In my opinion, this observation demonstrates the inherent advantage of hands-on projects over written problems: that students ascribe greater importance to projects that allow them to become truly involved in their learning, they achieve a greater sense of accomplishment with hands-on learning whether this learning is directly relevant to their field or not. Additionally, although I received some complaints concerning inter-group communication, overall I observed that most groups handled written communication nicely. I also observed that in several cases the need to complete understandable assembly and testing instructions led groups to think more carefully about the merits of simpler designs over exceedingly complex ones, which is a crucial consideration in the engineering design process.

Finally, I observed that most groups handled the creation of a mathematical model fairly well, although many needed to have the governing physical phenomena at work to be specified for them. Like myself as a freshman, I noticed that many groups were hesitant to take on such an open-ended problem; however, most groups in the honors section made appropriate assumptions. Looking at their project as a junior I realized how varied the possible complexity of a mathematical model could be and definitely gained a new appreciation for the ability to make necessary assumptions to solve an engineering problem with a given set of mathematical tools (many of my students had not yet completed calculus at the time of the project), which I hope they will also gain when they look back at their mathematical models as upperclassmen. I truly believe that the experience with their ENES 101 design project will benefit them in the future when they take on similarly open-ended problems as engineers.

Previous Design Projects: 2009

Design Problem and Constraints:

My most recent experience with the ENES 101 design projects was this past fall, during my second semester as a teaching fellow. In fall 2009, students were tasked with the design and construction of a heart and lung machine theoretically capable of maintaining blood flow, oxygen transport, and blood cooling during an open heart surgery. Each group's machine was judged based on its ability to maintain a biologically safe flow rate, achieve a specified minimum rate of oxygen transport, and achieve a specified rate of blood cooling. Once again, each group was required to build a mathematical model to predict their machine's performance prior to testing. However, given the complex nature of each heart and lung machine, groups were not required to create assembly and testing instructions and instead each group was responsible for the construction of its own machine. As a teaching fellow and a biochemical engineer I found this project extremely interesting because of the fact that it combines all three types of transport phenomena into a single design project.

Observations and Impressions from a Mentor's Perspective:

Once again, I observed that, although many students (particularly mechanical and computer engineers) initially believed this project to be irrelevant to their chosen major, once they began actually designing and constructing their machines their complaints ceased. Although I initially observed many more groups struggling with this design than with the hot air balloons, due to the somewhat unfamiliar nature of heart and lung machines, once the groups began to grasp the governing physical phenomena involved their designs began to turn out nicely. However, as mentioned previously, in this situation I believe groups would have benefited had they done some research on biological flow conditions (many groups used rapid spargers or external flows that would undoubtedly destroy blood proteins and kill the heart surgery patient).

Introducing Advanced Engineering Concepts in a Freshman Course:

The mathematical model for this project was particularly challenging as groups were expected to calculate convective heat transfer coefficients based on flow rates

within their systems using convective heat transfer correlations (a technique that is typically introduced in the junior level heat and mass transfer course). However, dedication of additional lecture time, in addition to a review session conducted by myself, was used to give students a basic understanding of this complex phenomenon. Based on my observations of students' level of understanding before and after the review session I believe that this extra time and effort was a worthy investment that allowed this year's freshmen engineers to gain experience with relatively advanced engineering calculations that they will undoubtedly encounter again in their upper level classes.

This observation is corroborated by data revealing a statistically significant difference between students' scores on the design project calculation portion of their final exam between the years of 2008 and 2009 [the scores were 46.07 % (n=182) and 55.11 % (n=167), and this increase in scores was statistically significant ($p = 3.18E-6$)], (despite the arguably more complex nature of the 2009 design calculation). [The faculty member believes that this was a direct result of the fact that the teaching fellow offered a review session prior to the final exam which was attended by approximately 70 students]. This trend is further corroborated by the fact that, on average, students rated their ability to design processes using engineering principles, their ability to use techniques, skills, and modern engineering tools, and their ability to analyze/solve open ended problems in engineering to be much higher in 2009 than in 2008, as seen in the data (Table 1 in Appendix A). Each of these increased ratings was statistically significant and the corresponding p values are also provided in Table 1.

Given the apparent success of this method of introducing freshmen engineers to advanced topics in engineering theory, I believe it would be beneficial to expect design groups to carry out more advanced engineering calculations in the future. Although it may demand extra time and effort to introduce students to topics of greater complexity, the freshmen engineering design project seems to be the perfect method of instilling abstract mathematical and physical concepts in the minds of young engineers by having them incorporate more advanced concepts into their mathematical models. I have no doubt that the chemical engineers from this past fall's ENES 101 class will have a much easier time grasping convective heat transfer correlations than my class did.

Tuning a Design during Prototype Construction and Evaluation:

This past semester's project also differed from previous projects in that many groups chose to spend much greater amounts of time in an available laboratory testing the various phases of their designs. Because the design criteria specified a very narrow acceptable temperature drop range many groups spent as much time as possible tuning their designs to achieve a desired result. As I was supervising many groups while they were using the available laboratory, I observed a dramatic increase in their ability to use laboratory equipment (pumps, spargers, power supplies, etc.) As this is the observed case I would greatly recommend giving freshman engineers more access to typical laboratory materials to use during the construction of their design projects, whatever they may be. I know for a fact that this acquired knowledge of fluid machinery will aid them greatly in their upper level engineering classes, especially fluid dynamics.

References:

1. Rice, J., T. M. Bayles, G. Russ, and J. Ross, "Preparing Freshmen for Future Energy Issues", Paper AC 2007-1748 published in the 2007 ASEE proceedings and presented in the Hands-on & Real World Studies Session in The Freshman Programs Division Session.
2. Carletta, J., Bayles T.M., Kalveram, K., Khorbotly, S., Macnab, C., Nazhandali, L., Rice, J., Smith, J.A., Turner, L.E., Williams, S. and L. Wyard-Scott, "Special Session – Real World Engineering Projects: Discovery-Based Curriculum Modules for First-Year Students", Paper accepted for publications in the Proceedings of the 39th ASEE/IEEE Frontiers in Education Conference; presented in session T1A, San Antonio, TX, October, 2009.
3. Bayles, T.M., "Project Based Learning Design Projects for Introduction to Engineering Design Courses", Paper #1381 published in 2005 ASEE proceedings and presented in the Freshman Programs Division Session – Problem Solving & Project-Based Learning.
4. Bayles, T.M., "Introduction to Engineering Design: An Emphasis on Communication", Paper AC-2009-1482 published in the 2009 ASEE proceedings and presentation in the Freshman Programs Division, San Antonio, TX, June 2009.