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WIP: Designing disciplinary projects in an honors first-year engineering course to improve retention and participation of first-year students.

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WIP: Designing multidisciplinary projects in an honors first-year course to broaden students' conception of engineering

Introduction

Engineering is a diverse discipline that incorporates knowledge from across academia. Yet there are certain images of engineering that have widely captured the imagination of popular culture of what an engineer is; images that most closely resonate with disciplines such as mechanical and civil engineering [1]. The tools of the engineer in students' minds are often closer to a hammer or a wrench rather than a test tube or beaker, and thus their conception of engineering is often limited at best [1]. This can get further complicated by the lack of interdisciplinarity exemplified in the engineering classroom. When engineering instruction is scaled at the university level, there is the potential to lose interdisciplinarity as well as too much emphasis on limited topics relevant to the field of engineering [2]. When this happens, the curriculum may revert to limiting the curriculum to the most popular images of engineering, fields such as mechanical, civil, and computer engineering [1].

The goal of this work is to look at how to broaden students' conception of the field of engineering in a first-years honor classroom at [omitted]. Currently, much of the curriculum is geared towards robotics, programming, and physics in the context of mechanical, civil, and computer engineering. As part of this research, new projects are being developed that intersect with a diverse range of fields of engineering, such as bioengineering, chemical engineering, biomedical engineering, environmental and ecological engineering, and industrial engineering. The expectation is that these projects will allow students to experience a more diverse look at the engineering profession in their first year and incorporate a deeper sense of belonging. As such, the research project has two main research questions: (1) In what ways does the incorporation of more diverse engineering projects broaden students' conception regarding the field of engineering as a whole? (2) In what ways does engineering identity change over the course of the semester when students are exposed to a diverse set of engineering projects?

Background

Engineering identity

One of the core pieces to education in any environment is whom you believe yourself to be and what you believe you are able to achieve. One way our study is hoping to achieve investigation into this is by looking at students' engineering identity. Morelock [3] found that there are many definitions for engineering identity used throughout the literature, ranging from what one perceives about the profession to the engineering actions one takes as an engineer. Other literature reviews have also identified definitions around communities of practice as well as the goals of an individual [4]. So, the definition used in the engineering education literature can vary.

For this study, a survey instrument from Patrick et al. [5] used to predict engineering identity and persistence is used. The survey is based on multiple previous instruments used to measure student outcomes such as the Sustainability and Gender in Engineering survey [6] and the

Academic Pathways of People Learning Engineering Survey [7]. The survey uses questions around performance, interest, self-reported identity, and recognition to predict both identity and persistence outcomes. The goal for using this instrument is to understand how interest, self-reported identity, self-reported performance, and perceived recognition change over the semester as student teams engaged in a diverse set of projects embedded in a classroom using project-based learning.

Project-based learning

Project-based learning has been heavily studied in the context of engineering education [8]–[11]. Project-based learning is an experiential form of learning, in which the basis of our learning is the sum of our experiences [12], [13]. These projects can look diverse in nature but generally follow a set of principles for designing effective learning interventions.

There are many different frameworks that have been proposed for project-based learning throughout the literature. One of particular note, Krajcik and Blumenfeld [12] have previously proposed a framework for project-based learning with five defining features: (1) an overarching question, (2) authentic contexts, (3) collaboration, (4) scaffolded learning, (5) artifact creation. Given the widespread use of this framework, it is these five features that are used in this study to design the projects for students throughout their first-year honors engineering experience.

Broadening participation in engineering

Throughout the engineering education literature the engineering classrooms are not nearly as diverse as they should be and certain groups are being left outside of the engineering pipeline into the university [14]–[17]. This lack of representation spans multiple categories including gender, race, and socioeconomic status. Because of this, much effort has gone into broadening participation within engineering, and more broadly STEM, education [17]–[19]. One study of particular note was conducted by researchers at Harvey Mudd who were able to increase female participation in their computer science program from 12% to 40% by redesigning their first-year curriculum [18].

Some of the changes we propose in this study follow the approach of Harvey Mudd College who combined experiential learning and opening up the curriculum to more interdisciplinarity allowed for broadened participation in their program [18], [20]. Our learning environment builds on their success by using experiential problem-based learning methods and introducing a broader view of engineering by including the biological, chemical, and environmental fields of engineering into the project-based learning design.

Project-Based Learning Design

In this section we overview the population of the course along with the current design of the projects. We then overview the details of the new design projects to implement into the course.

Population of the course

Students in a first-year honors engineering course at [omitted] are the focus of this study. Many of the students entering the course have already taken a significant amount of mathematics and physics at the high school level. The population is majority white and approximately 65% male/35% female, with the total breakdown approximating the demographics of the College of Engineering at [omitted].

Almost all students are experiencing their first semester at the university. Therefore, they have many of the same challenges as first-year students normally do such as moving to a new place, adjusting to a new educational environment, and the financial burden students can be under as well [21]. Additionally, given it is an honors course, the students now find themselves in a homogenous cohort of high achievers, something many of them have never experienced. This too may have an impact on their identity development as an engineering student.

Enduring outcomes of the course

Rather than list out learning objectives for the course, of which there are many, we have chosen here to report the enduring outcomes (EO) or enduring understandings we hope to achieve [22]. These are concepts that we hope the students retain long after they leave the walls of our class. These enduring outcomes are: (EO1) Engineers use the design process as a tool to ideate, create, evaluate, and refine engineering solutions, (EO2) Engineers solve complex real-world problems often by transforming them into algorithms that are solved computationally, (EO3) Engineers solve many problems using the universal accounting equation, (EO4) Engineers work in interdisciplinary teams using a universal set of tools to solve complex problems.

Sequence of projects

The sequences of projects in the course co-develop students' skills in teaming, modeling, and managing complex design processes. Project-based learning experiences are complex operations requiring the management of multiple subproblems that need to be identified, defined, and integrated together. The complexity of the projects is what engages students in a systematic design process which requires collaboration [23] and the use of tools to manage the research, analysis and communication of project results. The progression of design projects builds in their complexity and demand on team coordination. The sequence of projects begins with a simple, fun challenge, to build the teams' norms and workflow. Over a 10-day period the team designs, builds and tests a device to perform a function. The design constraints are defined by a scoring formula that involves multiple factors like task performance, cost, and weight. Teams demonstrated their device's performance typically in an evening event in front of a collection of their peers. They submit a final report describing their design process and final performance results.

The second project focuses on engaging students in modeling a system to estimate the feasibility of a large-scale system. The design task centers on developing a model the team can use to explore possible design alternatives for the system. The project leverages the previous instruction on Python programming as the tool of choice for modeling the system. Additional instruction is given to support students' understanding of the physical properties governing the behavior of the system. In addition, instruction is provided on how to approach the modeling process. The design constraints are organized around several possibilities to be considered. Each possibility requires balancing criteria and constraints associated with performance, cost, sustainability, and society.

Students present their ideas and results in a poster presentation format to their peers. They also demonstrate the design rationale for their model and how it can be used to explore other alternatives. Peers provide feedback on the content and presentation methods. Finally, the teams generate a final report summarizing their design of the model, their decision-making process for selecting the best alternative. Teams must provide quantitative evidence to justify their decision-making process and final selection.

The third, and final project, is a semester-long design process using mechatronic hardware. Currently, this hardware includes Lego parts for the physical structures and a Raspberry Pi computer with sensors and motors for mobility and actuation. The project is typically an automated vehicle performing a seek-and-act mission. The vehicle requires integrating multiple physical sub-systems like mobility, environmental sensing, cargo carry, and cargo release methods. The software subsystems involve navigation methods, mobile control, sensing, and other automated tasks. Teams engage in smaller design challenges using the hardware to help them learn how to interact with the hardware [23]. Like the other projects, teams test their prototype vehicle in a physical course where they need to demonstrate how they met various criteria. Their final performance is communicating their design rationale to their peers in a formal presentation. The final written report is submitted at the end of the semester.

Current projects

The course designers have experimented with a wide range of projects which this study is expanding to include more fields of engineering. Currently, the students do three different projects across the semester that tie to these enduring outcomes. Table 1 describes how each project maps to the enduring outcomes for the course.

Table 1. Current semester projects and how they map to enduring outcomes (**denotes focal point of topic for the projects).

Description	EO1 Design	EO2 Computation	EO3 Physics	EO4 Project Management
Project 1: Students design and build a catapult from a limited supply of materials.	**Students use and document their design process of the catapult and why decisions were made.	Evaluating scoring function to determine which design parameters to focus on.		Students manage a project as a team to explore potential solutions, select an alternative build, and test a device, while also communicating through a report.
Project 2: Students mathematically model a hydroelectric facility using Python.	Students use and document their design process of the open-ended problem of the facility design.	Assumptions are made about the facility and a Python script is generated to mathematically model system performance.	**Students leverage Newton's laws and the universal accounting equation to track mass and energy.	Teams manage model design process and report results both orally and written.
Project 3: Students design, build, and	Students use and document their	**Students practice different types of	Compute parameters	Teams manage prototype design

analyze a Mars rover system that can navigate variable terrain and drop off cargo.	design process of an extremely open-ended problem to come up with a totally unique design. Design involves the integration of multiple subfunctions.	obstacles/problems that must be converted into Python algorithms for their rover. Algorithms are used to navigate space with line following sensor and motor control. Cargo subsystem requires integrating other constraints which furthers the complexity that needs to be managed.	associated with scaling prototype rover from testing on Earth to testing on the Moon.	process and report results both orally and written.

Table 1 outlines the enduring outcomes covered at least once in each project. The progression scaffolds these outcomes through ever increasing complex sequence of projects. The projects tend to focus on physical devices and disciplinary associated with physical sciences. One reason for this selection is it has a level of accessibility to those new to design. Physical objects make it easy to rapidly explore new ideas which engages students in conversations and idea negotiation. However, the current projects limits the courses opportunity to highlight the interdisciplinarity of engineering and the universal nature of the problem-solving methods across disciplines. Therefore, more diverse contexts for the projects need to be explored across the course. Table 2 shows the disciplinary tags associated with each project which means an opportunity it being missed.

Table 2. Current semester projects and how they map to engineering disciplines.

Description	Related Disciplines
Project 1: Students design and build a catapult from a limited supply of materials.	Mechanical Engineering, Civil Engineering
Project 2: Students mathematically model a hydroelectric facility using Python.	Mechanical Engineering, Civil Engineering, Electrical Engineering, Environmental Engineering, Computer Engineering
Project 3: Students design, build, and analyze a Mars rover system that can navigate variable terrain.	Mechanical Engineering, Electrical Engineering, Computer Engineering

And while some of these disciplines benefit from the fact they are a bit more contextually independent, such as mechanical engineering, the instructional team felt that some disciplines such as bioengineering, chemical engineering, biomedical engineering, and industrial engineering, could use more coverage. This would be in hopes to show a more diverse image of engineering as a career choice.

New project designs

Alternative design options for project one and two have been developed. These options integrate practices from multiple engineering fields external to those traditionally ones represented in our classroom (See Table 2). Table 3 overviews a brief description of each project and the disciplines connects to each.

Table 3. Alternative project topics and disciplinary connections.

Description	Related Disciplines
Alternate Project 1: Students design and build a water filtration system from a limited supply of materials.	Mechanical Engineering, **Biological Engineering**, **Materials Engineering**, Environmental and Ecological Engineering (EEE)
Alternate Project 2: Students mathematically model their designed manufacturing process of converting corn into ethanol for E85 production.	Mechanical Engineering, Electrical Engineering, Environmental Engineering, Computer Engineering, **Biological Engineering**, **Chemical Engineering**, **Industrial Engineering**

Alternate Project 1 design: Designing a filtration system

The full Project 1 document is located in Appendix A. The background of the project reads:

> *Water is a source of life for everyone! Unfortunately, many populations in our current world don't have easy access to clean drinking water. Currently, about 17% of the world doesn't have easy access to safe drinking water. The problem is serious enough that it was listed as one of the 14 great engineering challenges of tomorrow. Your engineering team has been hired to work with the World Health Organization (WHO) to continue working toward possible solutions to this problem.*

The students are challenged with creating a water filtration device using simple materials such as plastic straws, popsicle sticks, plastic cups, and other household materials. This project has been loosely adapted from the *Water Filtration Challenge* proposed by NASA as part of their Engineering Design Challenges for education [24]. However, key additions were made to make the challenge more difficult for students at the honors undergraduate level.

Table 4. Alternative project one and enduring outcomes.

Description	EO1 Design	EO2 Computation	EO3 Physics	EO4 Project Management
Alternative Project 1: Students design and build a water filtration system from a limited supply of materials.	**Students use and document their design process of the water filter. Key design tradeoffs are identified between **speed, efficiency, and cost.**	Evaluating a scoring function where students must prioritize **recovery vs. removal vs. speed vs. cost vs reusability.**	**Basic mass balance required between original mass, recovered mass, and consumed mass.**	Students manage a project as a team to explore potential solutions, select an alternative build, and test the filter and then communicate in a report.

*Major updates are **bold.**

The biggest updates to project one are the addition of some physics into the system, even if the students don't realize it, they are doing elementary mass balances, something that will come back up later in the course. Additionally, the context has been added to give the students an authentic client (in this case the World Health Organization) as well as touches on engineering disciplines not seen in the original projects. The key focus on this project remains on the design process, where students are doing a basic design and looking at tradeoffs. Additionally, it functions to allow students to begin working and getting familiar with their teams.

Alternate Project 2 design: E85 production from corn product

The full Project 2 document is located in Appendix B, the background reads:

> *Biofuels provide an interesting opportunity that could be used to replace some of the more traditional fuels used in automobiles and manufacturing. However, to do so we must have more production facilities to convert biological and agricultural products into the fuels necessary to operate our world. [...] This project will focus on putting together an estimate for a small facility converting corn into the biofuel E85. Over the next several sessions we will research the issues and opportunities associated with one solution and then compare it with alternative solutions.*

The students, who at this point have learned basic mass and energy balances as well as introductory Python, are tasked with putting together a mathematical model of E85 production process and coming up with the process parameters with said model. Source materials for the development of the project have come from common biological and chemical engineering texts [25], [26]. This project will allow students to tie together all four enduring outcomes as seen in Table 5.

Table 5. Alternative project two and enduring outcomes.

Description	EO1 Design	EO2 Computation	EO3 Physics	EO4 Project Management
Alternative Project 2: Students mathematically model a conversion process of corn materials to E85.	Students use and document their design process of the open-ended problem of the facility design. **Increased ethical concerns are introduced in updated project.**	Assumptions are made about the facility and a Python script is generated to mathematically model system performance.	**Students leverage Newton's laws and the universal accounting equation to track mass and energy. **The mass balancing component has been increased from previous iteration.**	Teams manage model design process and report results both orally and written.

*Major updates are **bold.**

The biggest updates to Project 2 are around an increased focus on mass balances through the filtration and distillation processes, as well as additional ethical concerns incorporated into the design. While both of these were present in the initial design, they have been increased to be more emphasized throughout Project 2. Additionally, a different disciplinary context has been given that incorporates aspects of manufacturing design (IE) in a biofuel industry (BioE/ChemE) with increased awareness of sustainability (Environmental and Ecological Engineering (EEE)).

The key focus of project number two is EO2, having students develop and test an algorithm based off of their developed model.

Proposed Methods

Data collection

Survey instruments will be given to students at both the beginning and end of the semester to answer the two research questions. The survey instruments were developed and validated in previous studies in the literature for engineering identity [5] as well as student conceptions/perceptions of engineering [27]. First, this will allow instructors to understand who the students' see themselves as it relates to engineering and being an engineer. Additionally, it will allow the instructors to see what the students mean by the word engineer or engineering over the course of a semester.

Data analysis

Statistical analysis in the form of t-tests will be used for the quantitative analysis, while thematic analysis will be used to analyze the results of the qualitative data collection. Thematic analysis is a method by which large amounts of qualitative data are condensed into themes that best describe the dataset [28].

The goal of the analysis is to identify two sets of themes. The quantitative data will allow us to measure how student conceptions of engineering change after going through the designed projects during the semester. The qualitative data will allow us to track what themes emerge as to why students do or don't see themselves as an engineer after going through the designed projects.

Discussion and Conclusion

We anticipate that with enough iteration and implementation of alternative projects, we will be able to develop course materials that will help to broaden conceptions of engineering to include the full breadth of the field of engineering, which may help students situate their own identity into the field of engineering. The benefits of this are numerous, the biggest of which is that students who see themselves as engineers are more likely to stay in engineering [29]. To this end, it will allow us to understand how we might further broaden participation in engineering by opening up more perspectives of what is engineering using diverse contexts.

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Appendix A. Alternative Project 1 Design

ENGR XXXXX – Project 1: The Water Filtration Device

Background

Water is a source of life for everyone! Unfortunately, many populations in our current world don't have easy access to clean drinking water. Currently, about 17% of the world doesn't have easy access to safe drinking water. The problem is serious enough that it was listed as one of the 14 great engineering challenges of tomorrow. Your engineering team has been hired to work with the World Health Organization (WHO) to continue working toward possible solutions to this problem.

Overview

WHO has asked that you develop a simple prototype out of commonly accessible materials. To do this, your team will need to improve problem-solving skills and teamwork. There are some common materials that WHO has provided to you in order to build your prototype:

- 25 plastic straws; each straw is ~7 3/4" long
- 40 popsicle sticks; each popsicle stick is ~5 7/8" by 3/4"
- 1 roll of ¾ inch scotch tape
- 1 bottle of glue; volume of 4 oz
- 8 rubber bands
- One string ~9 ft long
- 10 plastic cups
- 70 grams of sand
- 20 coffee filters (only 1 can be used at a time in the design, the extras are for replacing after tests)
- 30 paper towels (2 at a time in your design)
- 35 cotton balls (5 at a time in your design)
- 70 grams of gravel

**You cannot use the bag the materials come in for the design, as you have to return unused materials in that bag.*
**You may not purchase or substitute materials for those which have been provided, even if you lose, cut, destroy, or otherwise mangle said materials.*

Your team will build a water filtration device that can:

1. Filter water with multiple different contaminants (how well can it filter?)
2. Filter water in a reasonable amount of time (how fast can it filter?)
3. Filter the majority of the water (how much of the water is recovered?)
4. Filter multiple water samples without needing part replacement (can it be used multiple times?)
5. Additionally, your team must design the system using as few of the given materials as possible (efficiency of design materials). Each design material that you use will have an associated cost with it.

The test of your device will be the following:

1. Your device must be able to filter a 10 oz water sample with varied contaminants. The 10oz will be poured into your device by a TA.
   a. Time starts the moment the TA starts pouring.
   b. Time ends when the water takes longer than 2 seconds to produce another drip.
   c. A color reading is taken after the filtration by the TA.
2. A second and third run will be made with the water filtration system.
   a. Nothing can be changed between the first and subsequent runs.
      i. This means no filter changes, no moving materials around, no readjusting the frame in any way, etc.
      ii. You should not have to touch your device in **any way** between runs 1, 2, and 3.
   b. The same measurements will be taken.

Your score will be according to the following:

$$Score = \frac{(\frac{avg\ weight\ recovered}{.625} * 100)^2 * \left(\frac{500 - avg\ color\ reading}{100}\right)^2}{(\frac{avg\ time}{60})^2 * (131 - unused\ resource\ points)}$$

Material costs sheet: You start with 131 points. Each material below costs points to use.

Material	Cost
Coffee Filter (1 per design)	50
Paper Towels	10 each
Sand	1 per gram
Gravel	1 per gram
Cotton Balls	2 each
Everything else given	Free

Demonstration

- Information regarding the date of the demonstration is available in the course syllabus. Information regarding the scheduled time for teams to participate in the demo will be posted on Brightspace during the week prior to the demo.
- A location for the demonstration has not yet been determined; however, it is almost certain to be held indoors.
- At demo check-in:
  - A PTA will analyze your device, looking for illegal elements.
  - You will turn in all your unused materials. Damaged materials are considered to be used and will not be included in the unused materials count.
  - A PTA will weigh your unused materials.
- Testing:

- Your device will be placed free-standing on a firm, level surface (e.g. hard plastic panel, MDF board, concrete, or tile). You will not be allowed to tape, hold, or otherwise manually support it in place. Only the weight and structure of the device itself can be used to keep it in place. See Additional Constraints below for more details.
- You will have 5 minutes to set up the device, from there, the PT or GTA will run water through the device and collect measurements.

Additional Constraints

- Team members cannot move or touch the device after initially setting it up. GTA's will pour in water and take all measurements.
- If any materials other than the ones given are used, you will be disqualified from participating in the event.
- You can modify the materials given to you. But if you modify a piece that costs points, regardless of how much of it you use, the full point cost will be deducted.
- If the device fails on the first test (falls apart to where water can no longer be poured into it, the subsequent two trials will count as if the water remained unchanged, with no mass recovered.
- Your group will be given 10 minutes total to run the demo (5 in prep, 5 in runs). Any additional prep time can be used for runs. If all three runs fails to finish prior to the time running out, any runs in progress will be stopped and measured from where they are, and any not started runs will be counted as the water remaining unchanged with no mass recovered.

Deliverables

A written Executive Summary will be submitted electronically. It is a one to one-and-a-half page summary highlighting the problem you solved, unique features of your filtering device, and a description of the performance of your filtering device design using quantitative evidence. Please note that any figures, tables, etc in your Executive Summary do not count towards the length requirement.

Appendix B. Alternative Project 2 Design

ENGR XXXXX – Project 2: Modeling Mass and Energy Balances

Grand Challenges Link: Energy and Sustainability

Overview:

Biofuels provide an interesting opportunity that could be used to replace some of the more traditional fuels used in automobiles and manufacturing. However, to do so we must have more production facilities to convert biological and agricultural products into the fuels necessary to operate our world.

However, this does not come without challenges, mainly infrastructure and efficiency during the conversion process. Many automobiles and pieces of equipment are not able to run off of the produced biofuels. Additionally, there is always energy loss from the raw material to the finished product and thus the agricultural product (corn for example), might have been put to better use in other parts of the economy.

This project will focus on putting together an estimate for a small facility converting corn into the biofuel E85. Over the next several sessions we will research the issues and opportunities associated with one solution and then compare it with alternative solutions. Accomplishing this task will require designing a computational model of our solution to assist in our analysis of the opportunities. Your team will conduct an analysis with your model to identify the most viable solution.

Project Proposal:

Your engineering consulting team is being hired by Fuel and Unusual Punishment Incorporated to investigate the production requirements for a small production facility for E85 (312,000 gallons/day, at least 97% by mass ethanol). The proposed system will convert corn into ethanol using the following process:

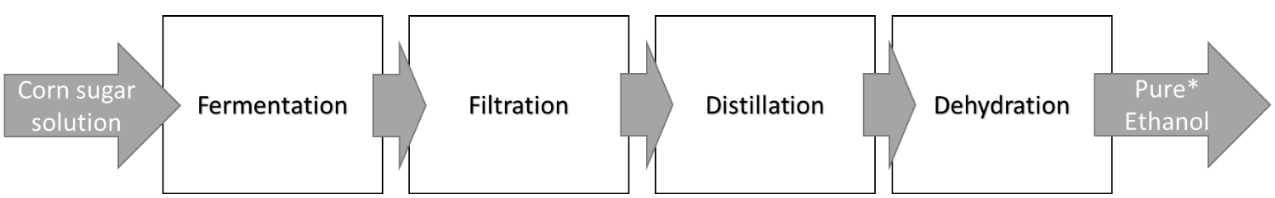

Figure 1. Overview of the production process. *Ethanol is not necessarily perfectly pure.

(1) **Input corn sugar solution:** Corn is crushed, diluted, and given an enzyme to liquify the material. Another enzyme is added at this step to convert starches to sugars. The material arrives to your facility in this state (consists of 20%wt sugar, 60%wt water, 20%wt insoluble corn fiber).
(2) **Fermentation:** Add yeast and convert sugars in liquid into an alcohol solution.
(3) **Distillation:** The alcohol solution is run through a still to extract the alcohol (the contaminants should remain in the same concentration).

(4) **Filtration:** The alcohol (ethanol) is filtered to get rid of organic materials.
(5) **Dehydration:** Excess water is removed.
(6) **Output pure ethanol:** Which can be converted to E85 (by adding gasoline) at another facility (98.5 %wt pure ethanol, 312,000 gallons/day).

However, there are multiple old facilities that can be used for this project as well as multiple different pieces of equipment and materials that can be used. This wide range of choices provides an opportunity for arriving at an economical solution to the storage problem that can be competitive with other fuel and ethanol production facilities in the area.

The company needs a well-defined feasibility study to support its decision-making. They would like a highly sophisticated model of the system so that they can evaluate various tradeoffs of cost and efficiency. The designed system should be able to produce 312,000 gallons/day of 98.5 %wt ethanol and be as energy efficient as possible, this is a biofuel facility after all! However, the company would also like to try and minimize cost as well and is willing to pay your team a bonus for a minimally costing energy efficient system.

As part of their contract with you they will be expecting an oral presentation of your findings with an opportunity for questions and answers. Further, they will need a detailed report of your analysis for their technical team to review. The technical team will also need access to your notes as validation of your analysis methods and inquiry methods.

Key Assumptions:

1. Assume all tanks are operating at steady state, which is to say, the internal volume is not changing with time (think about what this means in terms of flowrates for your system).
    a. Are tanks are completely filled from the start.
2. Pipe areas are always constant, so water velocity is always constant (approximately) in pipes.
3. Pumps and unit ops will always output a constant volume of water per unit time.
4. The pipes are full of water before and after any mass or energy accounting.