AC 2008-399: A FIRST-YEAR ENGINEERING EXPERIENCE IN SUSTAINABLE DESIGN

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A First-Year Engineering Experience in Sustainable Design

Abstract

For the past fifteen years, Brazil has been producing fuel ethanol from sugarcane, thereby decreasing their overall gasoline consumption by 50%. With decreasing oil supplies and increasing fuel costs, many countries hope to duplicate Brazil's success. However, sugarcane, the ethanol staple crop in Brazil, does not cultivate well in other climates. Therefore, an effort must be made to determine the process feedstocks for different regions of the world. In the Spring of 2008, first-year engineering students at Michigan Technological University will investigate the potential of fuel ethanol produced from lignocellulosic (woody) biomass.

During the course of this project, students will utilize the "waste equals food" principles of sustainable design outlined by William McDonough and Michael Braungart. Using these guidelines, students will learn to incorporate the principles of sustainable development in the design and simulation of an ethanol production facility. They will investigate the sustainability of the production of the ethanol *product* from a regional feedstock and the sustainability of the ethanol *process* by developing a facility to eliminate waste from the production process.

This paper will describe the incorporation of the biomass-to-ethanol design project into our first year engineering program, the assessment methodology used and the expected educational outcomes of the project.

Introduction

All first year engineering students who enter our program Calculus-ready take a two semester course sequence: ENG1101 (Engineering Problem Solving and Analysis) and ENG1102 (Engineering Modeling and Design). These courses are designed to introduce first year engineering students to basic engineering topics: 3D visualization and modeling, ethics, engineering design and problem solving, software proficiency, and technical communications. In the second semester course, ENG1102, students complete a semester-long design project within an engineering team of 3-5 people. In the past, these design projects have included: an autonomous robot, a human-hybrid vehicle, a New Orleans flood management plan, a microbrewery and a super mileage concept vehicle.

Beginning in the spring semester of 2008 is the alternative fuels design project where students will examine the viability of a biomass-to-ethanol process using regional timber resources (logging residues or energy crops such as hybrid poplar). With increasing pressure to reduce foreign oil consumption and the U.S. Department of Energy looking to increase the biofuels usage from 3% to 30% by 2025, this is a current problem graduating engineers may be called to investigate.[1] The goals of this new design project are to: a) encourage the development of engineering skills (graphical and technical communication, and computer proficiency) b) introduce students to a "real-world" engineering problem and c) apply the concepts of sustainability toward an engineering solution. Upon completion of the project, students will have:

1. Evaluated the technical and economic feasibility of a biomass-to-ethanol facility in Michigan's Upper Peninsula,
2. Calculated the resource requirements of the facility to quantify the sustainable timber harvest from the local forests,
3. Developed a comprehensive resource budget for energy and materials used in the process,
4. Created a simulation program to track the energy and material flows throughout the production facility, and
5. Identified ways to eliminate waste byproducts from the production of ethanol from woody biomass.

Challenges of Biomass-Ethanol Fuels

Biofuels present unique challenges with respect to their conversion from biomass to fuel and the conversion efficiency of the process. Brazil has achieved success with their biofuels program using sugarcane as the staple crop. Sugarcane grows well in the southern regions of the United States, but it does not cultivate well in more northern climates. In the regional community surrounding Michigan Tech, one of the most pressing problems has to do with the composition of the available biomass feedstock: timber. Cellulosic material such as timber is primarily comprised of three main fractions: lignin, cellulose and hemicellulose. Cellulose and hemicellulose can be converted to ethanol, while lignin is mostly insoluble and is not converted.[2] In addition, bacteria capable of fermenting both cellulose and hemicellulose sugars are developed through the use of recombinant DNA technology as the original strains cannot ferment both sugar types.

A second concern is the conversion efficiency from biomass to ethanol. Typical conversion factors for this process are: 60-70% of biomass is cellulosic or hemicellulosic material, 75-80% conversion of cellulosic material to sugar and 85-92% conversion of sugar to ethanol leads to an overall process efficiency of approximately 50%.[2,3,4] When looking at this kind of process efficiency, two major questions arise: is a biomass-to-ethanol process using lignocellulosic biomass as a feedstock a sustainable solution? If not, what can be done to make this process a viable long-term alternative to fossil fuels? As part of their ENG1102 experience, Michigan Tech students will answer these questions.

Biomass-to-Ethanol Facility

The basic design for the biomass-to-ethanol facility for the alternative fuel design process is based upon an ASPEN Plus Simulation developed by National Renewable Energy Laboratory (NREL) in 1999. This process, shown in Figure 1, uses yellow poplar as a feedstock and consists of 9 main process areas: feed handling, pretreatment, fermentation, enzyme production, purification of product, wastewater treatment, product and chemical storage, waste combustion, and utilities.[3] Wood is reduced to chips in the feed handling area and then fed to a pretreatment unit, where dilute sulfuric acid converts hemicellulose to sugars. The sugars and remaining biomass are fed to the fermentation section where microorganisms and enzymes convert the all the sugars, including cellulose sugars, to ethanol. The fermenter broth is separated in the wastewater treatment area into a pure ethanol product, water recycle stream, and residual biomass byproduct. The residual biomass byproduct is combusted to generate steam and electricity for use in the process as well as to export excess electricity to the grid (where it could displace electricity from coal, a "carbon- intensive" energy resource).

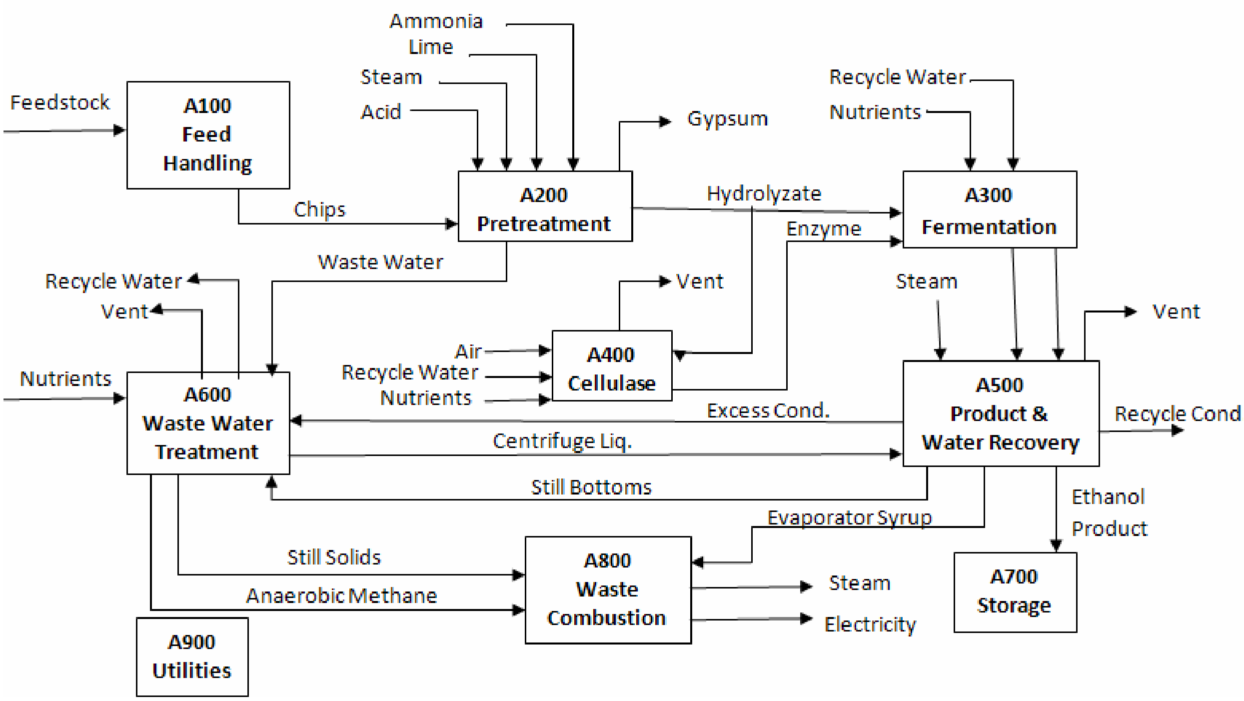

Figure 1. NREL Cellulosic Biomass-to-Ethanol Process (Adaptation)[2,3]

Due to the background knowledge of the students and the time constraint of one semester, the process was reduced to only essential components. This modified process, shown in Figure 2, consists of four main process areas (pretreatment, fermentation, purification of product and storage). Enzyme production, chemical storage, wastewater treatment and waste combustion have been eliminated. In addition, there are several recycle loops and heat integration options that were removed to further simplify the process. Students will be investigating alternatives to waste treatment and combustion and these will be discussed in a later section. In order to create a sustainable product, students will scale the plant size to produce approximately 155.3 MM gallons of ethanol annually to meet the needs of the regional community.[6]

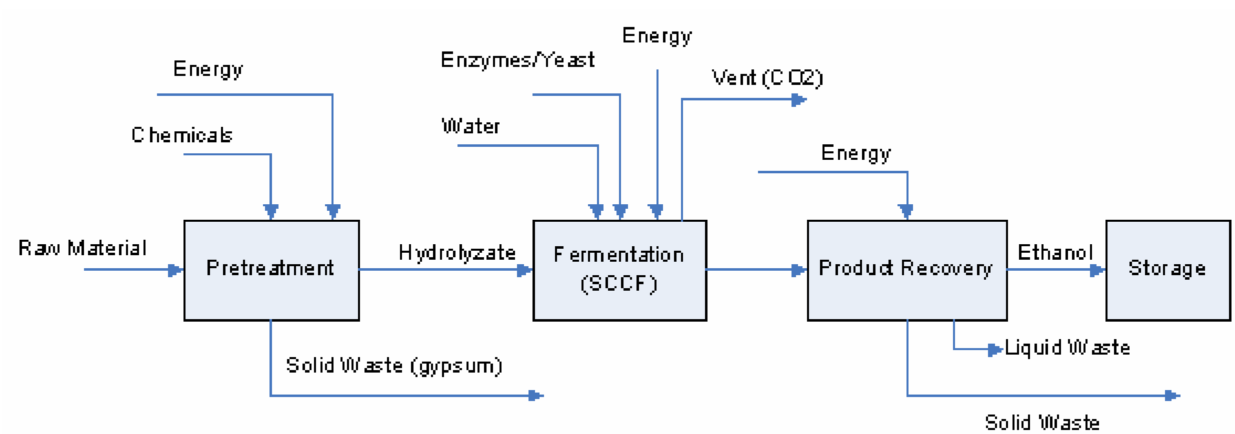

Figure 2. Simplified Biomass-to-Ethanol Process

Resource Requirements

As part of their project, students will estimate the land area required for sustainable production of ethanol from U.P. Timber and monitor the resources (mass and energy) necessary to produce the amount of ethanol required to satisfy local demand. The first step, determining the land area, requires that the students calculate what is considered a sustainable harvest from the regional timber resources. It is expected that students will discover that in order to produce the amount of ethanol required, the plant will consume approximately 1.3 MM dry tons of biomass per year, which could be obtained by using currently available and unutilized forest residue (i.e sawmill, logging, thinning or pulp mill residues).[5]

Another harvesting option which students may choose to investigate would be the use of a hybrid crop such as poplar or willow to satisfy the needs of the facility. In this scenario, students would determine the sustainable harvest for the crop (4-10 dry tons/acre ·year)[6] and would then calculate that the land required to grow the biomass for the facility would be approximately 0.13 – 0.33 MM acres (approximately 1.2%-3.2% of the U.P. land area).

Students will also develop a resource budget to track energy and materials used in each area of the process. For example, students will monitor the conversions from biomass to sugar and sugar to ethanol as they occur throughout the prehydrolysis and fermentation areas of the biomass-to-ethanol process. In addition, they will determine the energy requirements for the process. For example, they would calculate the steam used in the prehydrolysis area to convert the hemicellulose fraction to pentose sugars.

Simulation Program

Using the mass and energy data they collect, students will develop a simulation program of the ethanol production facility using Matlab. Students will be able to validate their simulation results through a comparison with the NREL simulation for a lignocellulosic biomass-to-ethanol process using a yellow poplar feedstock.[3] Student simulations will walk through the production process, beginning in the prehydrolysis area and finishing when the ethanol is moved into the storage area. In each step of the process, the programs will track the mass and energy inputs/outputs and deliver an updated report to the user. For example, student programs will monitor the conversions of the cellulose and hemicellulose fractions to hexose and pentose sugars and then the resultant conversions to ethanol. They will monitor the growth of the microorganism (*Z. mobilis*) throughout the fermentation process and show how the organism moves through the different life-cycle phases: growth, stationary and death/decline. An example growth curve that student programs may output can be found in Figure 3.

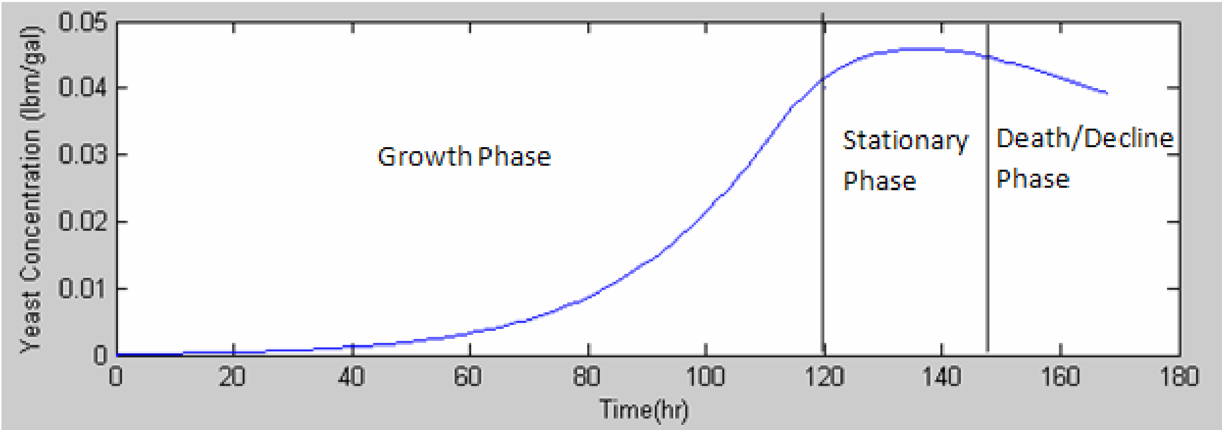

Figure 3. Typical Growth Curve for a Bacterial Population

Elimination of Waste

"*To eliminate the concept of waste means to design things – products, packaging and systems – from the very beginning on the understanding that waste does not exist.*" [7]

The "waste equals food" principle in effect looks at two distinct cycles: biological and technical. An example of a biological cycle would be the carbon cycle. In this cycle, plants grow and take up carbon dioxide and store it until they decompose and release it back to the environment. A technical cycle is more complicated and looks at industrial products such as a computer. A computer contains mutagens, carcinogens, toxins that could have a damaging effect on the environment should they be directly released.[7] In general, the "waste equals food principle" states that anything that is currently considered waste should have the potential to become food for something else. This can be simplified by stating the following: products should be designed so that they can go back to nature (i.e. be 100% biodegradable) or be completely reclaimed by industry.

One of the primary objectives for this design project is to apply the concepts of sustainability toward an engineering solution. In order to improve the sustainability of the biomass-to-ethanol process, students will incorporate sustainability into their overall design decisions by looking for opportunities to reduce energy consumption, improve process efficiency and eliminate wastes. Looking back at Figure 2, there are raw materials, waste and energy streams associated with each step in the biomass-to-ethanol process. A major goal of this project is for students to identify ways to eliminate waste streams from the biomass-to-ethanol process. Students will be utilizing the "waste equals food" principles of sustainable design in order to create a sustainable solution.

For example, students may see the solid waste gypsum exiting the prehydrolysis area and determine that this "waste" could be used as a raw material to create blackboard chalk, cement, wallboard or Plaster-of-Paris.[8] The lignin portion of the feed could be separated out and used as an adhesive, emulsifier or used to sequester metal ions.[9] Students might decide to use renewable solar power for electricity rather than relying on electricity from a coal-burning power plant.

Assessment

In order to assess student learning from the design project a pre- and post survey will be administered. The pre-survey will be given prior to the introduction of the design project and the post survey completed after their final project book has been submitted. The survey will contain ten essay questions and will be used to determine the student's knowledge of bioprocessing, alternatives to gasoline, sustainability and alternative energy. A complete set of questions can be found in Table 1 below.

Table 1. Pre/Post Survey Questions for Assessment

Topic	**Question**
Bioprocessing	• Define biomass. • Define a bioprocess • Provide an example of bioenergy and a bioproduct.
Gasoline Alternatives	• Explain fuel alternatives to gasoline that are currently available. • Explain fuel alternatives to gasoline that are projected to become available. • Explain the limitations to gasoline alternatives.
Sustainability	• Provide a definition of sustainability and explain the concept of sustainability by providing a concrete example. • Describe the characteristics of a sustainable engineering design.
Alternative Energy	• Provide examples of alternative energy sources. • Explain the short/long term costs and benefits are for alternative energy.

At the end of the semester, students will complete a 12-question survey to assess their perception of: a) the overall design project, b) how the project related to their major, c) how the project improved their understanding of sustainability and d) the project's applicability to their upper division courses. The survey uses a 5-point Lickert Scale and will be completed after the students submit their design project books. The survey results from students completing the biomass-to-ethanol project will be compared to those in sections with the microbrewery design project.

The micro-brewing project serves as an ideal comparison for a number of reasons:

- The differences in course material are minimized as the micro-brewing process also focuses on creating a sustainable design,
- It utilizes the "waste equals food" principles to eliminate process wastes, and
- The brewing process is another example of a bioprocess.

These two design projects were mainly developed to target chemical and environmental engineering majors so the student demographic should be similar. In addition, the instructor for both projects is the same, which eliminates variations in teaching style that could affect student perceptions of the course material. The only disadvantage is that the micro-brewing process has been taught for three semesters, while the biomass-ethanol project was first taught in the spring 2008 semester.

Expected Educational Outcomes

As mentioned previously, the goals of the alternative fuels design project are to: a) encourage the development of engineering skills (graphical and technical communication and computer proficiency) b) introduce students to a "real-world" engineering problem and c) apply the concepts of sustainability toward an engineering solution. The tasks outlined in the paper have been specifically directed at satisfying the third goal, but the other two goals are satisfied as well.

Throughout the course of this project, students will document their progress to the instructor through the use of memos, spreadsheets, presentations and reports, thereby increasing their technical communication skills. They will develop a 3D model of the plant layout with the various unit operations to improve their graphical communication skills. These tasks and their simulation program will increase their computer proficiency.

Finally, students will develop a sustainable biomass-to-ethanol process by a) determining the renewable biomass requirement of the facility to make sure the regional community can support the plant, and b) identifying ways to eliminate waste byproducts from the production of ethanol from biomass. At the conclusion of their work, students will have determined the feasibility and potential limitations or challenges of the biomass-to-ethanol facility in Michigan's Upper Peninsula.

It is expected that the overall student knowledge base on bioprocessing, alternatives to gasoline, sustainability and alternative energy will be greatly expanded through the completion of the biomass-to-ethanol design project. After reviewing the 12 survey questions, the students in the micro-brewing section might have a higher overall rating of the micro-brewing project than the biomass-to-ethanol project as this is the first semester the biomass-to-ethanol project was taught. Also, chemical and environmental majors will most likely perceive both topics as more relevant to their majors than other engineering majors. For future course offerings, student comments and perceptions will be taken into consideration in order to improve the biomass-to-ethanol and micro-brewery projects.

Bibliography

1. Halford, Bethany "Fields of Fuel" ASEE PRISM November 2006.
2. Kemppainen, Amber J., Comparative Life Cycle Assessments for Biomass to Ethanol Production from Different Regional Feedstocks. MS Thesis Michigan Technological University, 2003.
3. Wooley, Robert, Mark Ruth, John Sheehan, Kelley Ibsen, Henry Majdeski and Adrian Galvez. "Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis Current and Future Scenarios." NREL/TP-580-26157 July 1999.
4. Ingram, L. O., et al. "Enteric Bacterial Catalysts for Fuel Ethanol Production." Biotechnology Progress, v15 n5, 1999. pg. 855-866.
5. Froese, Robert. Biomass for Biofuels in the Michigan Upper Peninsula. MEDC visit March 16, 2007.
6. Tuskan, Gerald. Oak Ridge National Laboratory. "Fact Sheet: Short Rotation Woody Crops." http://bioenergy.ornl.gov/ Web Accessed January 2008.
7. Mc Donough, William and Michael Braungart. Cradle to Cradle: Remaking the Way we Make Things. North Point Press, 2002.

8. Spectrum Analytic. http://www.spectrumanalytic.com/support/library/rf/Gypsum.htm. Web Accessed January 2008.
9. Lignin Institute. www.lignin.org. Web Accessed January 2008.