Biorefineries

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Executive Summary

A biorefinery uses biomass feedstock to produce valuable chemicals and resources that can be used in many applications, including alternate energy sources such as fuels by means of an integration of many processes with the objective of producing many products. By incorporating many different processes into one refinery under one roof, power, energy, utilities, and maintenance costs can be shared and conserved.

Choosing the processes that are the most economical and profitable is a main focus in this project. Starting with one large superstructure of different processes, the net present worth of each of the processes is to be compared and those processes which are unprofitable, eliminated. A mathematical model is constructed to eliminate processes and choose capacities and expansions. In this mathematical model the equations for net present worth, fixed capital investment, operating costs, demand, capacity restraints, material balances, sales, revenue, and material costs, are included. To eliminate the first round of processes, the assumption was made that the operating costs were all equal to zero. From here, based on the inputs and outputs only, the superstructure was narrowed down to a smaller form.

In order to accurately calculate the net present worth, various parameters had to be calculated. By running simulations on each process, the operating costs and fixed capital investments for the processes are found. From these findings, the parameters are used in the model. The market demand and material costs for the chemicals are other parameters that are put into the formulation. These values help to compare the processes to ensure that the decision made is the most economically optimal outcome.

The model that is created produces results for very complex problems, such as narrowing down more than 16 million options of different operating conditions. After designating the parameters, the model only takes 90 seconds to run, and gives the optimal results of the investment.

After the model is running correctly, several case studies are done for different situations. If the initial investment is five million dollars, the model shows us that the NPV is 27.5 million dollars. With a twenty million dollar investment, the model gives an NPV of 24.5 million dollars. The variable investment study, the model picks the best investment by optimizing the trade off between how much we can build in our first year and how much in interest charges we have to pay back at the end. With this option, the model chooses 7 million dollars to be investment, and has a NPV of 28.8 million dollars.

Several things are recommended as further analysis into the projected biorefinery. Location of the biorefinery has a large impact on the fixed capital investment as well as the operating costs. This must be considered when deciding upon the profitability of the refinery. The choice of feedstock must also be carefully considered; whereas, the biomass must be able to be converted to the desired products in the chosen processes.
Introduction

Biomass energy is the use of organic matter as alternate energy, fuels, or chemicals. The organic matter is processed and converted in a biorefinery[1] The energy problem that is currently facing the world is one of the motivating factors for building biorefineries in the near future. The need for renewable energy sources such as biofuels and other chemicals is increasing quickly, and biomass conversion into these products is a pliable solution. The basic concept of designing a biorefinery is to select the material that will be put into the refinery, decide on the conversion processes, and pick the desired products along with a timetable for construction and investment.

Different types of biorefineries use biomass from varying sources to form chemicals. The most universal process of conversion is fermentation of sugars. Fermentation can produce many other products besides biofuels, including lactic acid, succinic acid, acetic acid, tetrahydrofuran, and other food additives and organic solvents that can be very marketable. Other types of conversions are used as well in a biorefinery, such as hydrolysis, gasification, and thermal conversion in a reactor.

Project Purpose

The purpose of our project is to compile a mathematical model that will narrow down a super structure of process options and will choose the optimal operating conditions, such as capacity and expansions. With a limited amount of money to spend on the initial investment, every process may not be able to be built in our biorefinery. Narrowing this down involves much analysis.

As we will illustrate, integrating many different processes into one location to be refined will dramatically decrease the cost of operating the plant. Similar to petrochemical refineries, our goal is to produce high-volume liquid transportation fuel, helping energy needs, and valuable chemicals and products.

Some advantages that are not solely financial are also involved in the biorefinery. Many forms of biomass come from material that is generally either thrown away or released into the atmosphere. For example, corn stover and black liquor have no purpose in their respective industries. However, instead of throwing these away (corn stover) or releasing them into water sources and rivers (black liquor), these things can be processed into organic matter which can be converted into chemicals. Not only will this help reduce the amount of waste that is put into landfills, burned, or disposed of in other ways, it will decrease the amount of water pollution and other types of pollution.
Background

Biorefineries

Many types of biomass, the organic and inorganic matter, are found in the United States as well as throughout the entire world. Some examples of types of feedstock that are commonly used as biomass are corn, grains, wood products, grass, straw, and black liquor. The most commonly used processes for refining biomass uses fermentation to convert the sugars into chemicals, but then many of the products must be put into another reactor or distiller to further convert into desired products. Figure 1 is a diagram that shows many of the materials and chemicals that can be produced in a typical biorefinery. Several of the feedstocks, processes, and products are shown in order of the production.

![Diagram of Biorefineries](image)

Figure 1: Basic Principles of Biorefineries [1]

Integrated Biorefineries

Some biorefineries produce only one product. These are the simplest refineries that only involve one or two processes. However, by incorporating many different processes into one refinery under one roof, power, energy, utilities, and maintenance costs can be shared
and conserved. For example, if one power and steam plant is used for 10 different processes in a refinery, there will be a considerable amount of money and utilities conserved.

The following table is a summation of several of the goals for biorefineries in the next 20 years [1]. Sharing of utilities should save at least 5% use of electricity and heat demand in industry. In the future, biofuels should contribute to at least 20% of the demand for transportation fuels, and bioproducts should count for 25% of shared chemicals.

Table 1. The United States national vision goals for biomass technologies. *Quads* Energy units, based on the British thermal unit (BTU; 1 kW h⁻¹); 1 quad = 1 quadrillion BTU (10¹² BTU)

<table>
<thead>
<tr>
<th>Technology</th>
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<td>(2.7 quads)</td>
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<td>(4.0 quads)</td>
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<td>4%</td>
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<tr>
<td></td>
<td>(1.0 quads)</td>
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<td>(4.0 quads)</td>
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<td>4%</td>
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<tr>
<td></td>
<td>(0.15 quads)</td>
<td>(1.3 quads)</td>
<td>(4.0 quads)</td>
<td>(9.5 quads)</td>
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<tr>
<td>Bioproducts</td>
<td></td>
<td>5%</td>
<td>12%</td>
<td>18%</td>
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<tr>
<td>Share of target chemicals that</td>
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<td>5%</td>
<td>12%</td>
<td>18%</td>
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<tr>
<td>are biobased</td>
<td></td>
<td></td>
<td></td>
<td>25%</td>
</tr>
</tbody>
</table>

[7]

This shows the benefits of having shared utilities, having alternate energy sources, and also many more chemicals that are all derived from bio-based materials. Not only will the integrated biorefinery help preserve energy and save money, the demand of fuels and biobased chemicals can be met as the generation moves toward a bioeconomy.

**Depleting Fossil Fuels**

The depleting amount of fossil fuels has become a major issue in the world in this century. As the fossil fuel resources quickly come to an end, there is a demand for alternate sources of fuels, such as ethanol, biodiesel, and other biofuels. Fossil fuels are the primary source of energy today. 85% of our energy demands come from combustion of fossil fuels [4].

Many of the countries will have utilized all of their sources of oil and natural gas in the next few years, or at most the next century. As figure 1 shows, the United States will be depleted of fossil fuel resources in the next 6-12 years. The rest of the world is not too far behind the United States. Efforts must be made to conserve the remaining fuel by maximizing the fuel potential. Alternate energy sources are needed to heat/cool/light our houses, run our cars, and just maintain the way of living that we are accustomed to. According to the department of energy, ethanol is expected to eventually supply 30% or more of U.S. transportation fuel needs.[5]
Figure 2: Map of oil reserves[6].

Another issue associated with the burning of fossil fuels is the amount of greenhouse gases that are produced. Global warming is becoming a massive problem for the entire world and should not be taken lightly. Burning fossil fuels releases carbon dioxide into the atmosphere which is the main gas that is causing this increase in mean global temperature. “The incineration of waste plastic made from petroleum also releases carbon dioxide into the atmosphere.” [7] By using fuels that do not emit carbon dioxide or have a net carbon dioxide emission rate of zero and reducing the use of petroleum directly can help decrease the problem.

Products

High-value chemicals can be produced from biomass feedstock, and many of these chemicals and products are in great demand in numerous industries. Some chemicals that are produced in biorefineries include ethanol, methanol, biodiesel, glycerin, biogasoline, acetic acid, ethane, ethyl lactate, diactide, lactic acid, acetic acid, acrylic acid, polymers and monomers, succinic acid, diphenolic acid, and levulinic acid.

Figure 2 shows our projected product tree. Each box is a process, and inside the boxes are the different products that are produced from the respective processes. Some of the products from processes are going to be sold for profit. Other portions of the products are put through another process for further conversion into other chemicals. For example, ethanol can be either sold, or put into three other processes to produce ethyl
lactate, acetic acid, or ethane. Many decisions must be made to decide which processes to build, and what portions of each chemical to sell or to put into another process.
Process Selection

Starting with a very large outline, like the one above, many paths could be taken to choose the most profitable scenario. The processes that begin with glucose are put into the fermenter and converted into lactic acid, ethanol and acetic acid. From here, products are put into either reactors, distillers, or sold for profit. The lignin is put into a gasifier to produce syngas, and further converted into gasoline, methanol, glycerol, and biodiesel in several different kinds of reactors. Levullinic acid is also produced by fermenting sugars and further conversion can be done to produce succinic acid, tetrahydrofuran, and diphenolic acid. Some fermentation reactions that take place are listed below:

**Acrylic Acid**

\[ C_3H_6O_3 \rightarrow C_3H_4O_2 + H_2O \]

(lactic acid) (acr. Acid)

**2,3-Pentadione**

\[ 2C_3H_6O_3 + \text{acet. acid catalyst} \rightarrow C_6H_8O_2 + 2H_2O + CO_2 \]

(lactic acid) (2,3Pent)

**Ethyl Lactate**

\[ C_3H_6O_3 + C_2H_5OH \rightarrow C_2H_{10}O_3 + H_2O \]

(lactic acid) (ethanol) (ethyl lac)

**Acetic Acid**

\[ C_6H_{12}O_6 + 4O_2 \rightarrow CH_3COOH + 4CO_2 + 4H_2O \]

(glucose) (acetic acid)

**Succinic Acid**

\[ C_6H_{12}O_6 + 5.5O_2 \rightarrow C_4H_6O_4 + 2CO_2 + 3H_2O \]

(glucose) (succ. acid)

These processes are all commonly used steps to produce the desired outcome; however, some might not be economical. For example, the fixed capital investment and operating costs that are involved in producing lactic acid are more than the money you would make
over the lifetime of the project, then the process should not be built. Furthermore, if the demand for lactic acid went drastically down, or even to zero, then the amount of money made, or revenue, from the lactic acid would not be enough to justify running the process. By creating a mathematical model to eliminate some processes, the best choice of products and processes are chosen, as is shown in the next section. The processes in the above diagram were narrowed down further after careful consideration.

**Mathematical Model**

When planning the construction of a biorefinery, there are a large number of different chemicals that may be produced. The interrelations between different processes within the biorefinery can become complex very quickly. A general model has been developed for the description of a traditional chemical refinery [8]. The goal of the final design is to maximize the net present value (NPV) of the project given some amount of money that may be invested. The resulting solution should define how the biorefinery should be operated over the project lifetime and for this purpose, a mathematical model has been developed.

\[
\text{NPV} = \sum_i \left( \sum_j \text{revenue}(j, t) - \sum_i \text{operating cost}(i, t) - \sum_i \text{FC}(i, t) \right) \cdot \text{df}(t) \tag{1}
\]

Throughout the model description, the index \(i\) refers to a particular process and the index \(j\) refers to a chemical component that is used within the refinery. The refinery is modeled over discrete time periods, \(t\), during which the operating conditions do not change. The quantity \(\text{df}(t)\) is a discount factor that accounts for the changing value of money over time. \(\text{FC}(i, t)\) refers to the fixed capital investment for a particular process within the biorefinery for some time period.

\[
\text{FC}(i, t) = \alpha(i) \cdot Y(i, t) + \beta(i) \cdot (\text{initial capacity}(i, t) + \text{expansion}(i, t)) \tag{2}
\]

The variable \(\text{initial capacity}(i, t)\) represents the capacity of process \(i\) that is first built during time period \(t\). Likewise, \(\text{expansion}(i, t)\) refers to an expansion of the process during some other time period. \(Y(i, t)\) is a binary variable that assumes either a value of 0 or 1 if process \(i\) is built or not built during time period \(t\). Some constraints will be presented to control how this variable may change over time. The fixed capital investment costs are modeled linearly using parameters \(\alpha(i)\), which is the penalization for starting construction on a new project, and \(\beta(i)\), the incremental charge that is related to the total capacity of a process.

The capacity of a process is restricted by both a minimum and maximum capacity. To prevent a process from being built that would only be profitable outside these ranges, the capacity must obey the following rules which will determine the value of \(Y(i, t)\).

\[
\text{initial capacity}(i, t) - Y(i, t) \cdot \text{max capacity}(i) \leq 0 \tag{3}
\]

\[
\text{initial capacity}(i, t) - Y(i, t) \cdot \text{min capacity}(i) \geq 0 \tag{4}
\]
In addition to the initial construction of each process, expansions may be performed in the future time periods to increase the capacity of the process. To govern the expansion of each process, a constraint similar to the one above is introduced.

\[
\text{expansion}(i, t) - X(i, t) \cdot \text{maxexpansion}(i) \leq 0 \quad (5)
\]
\[
\text{expansion}(i, t) - X(i, t) \cdot \text{minexpansion}(i) \geq 0 \quad (6)
\]

Multiple conditions are imposed on both the construction and expansion process.

\[\sum_i Y(i, t) \leq 1 \quad (7)\]
\[X(i, t) + Y(i, t) \leq 1 \quad (8)\]
\[\sum_{i' \leq i} Y(i, t') \geq X(i, t) \quad (9)\]
\[\sum_i X(i, t) \leq \text{NEXP}(i) \quad (10)\]

This constraint ensures that the initial construction of each process only occurs once during the lifetime of the project. Additionally, the expansion cannot occur in the same time period that construction takes place. The expansion of a process cannot occur until the process has been built and finally, the number of expansions a process may undergo is limited by the final constraint.

Next, the input and output from each process must be specified. There are two types of inputs into each process: raw materials that must be purchased, and materials that can flow from one process to another. In the equation below, the variable flow(k,i,j,t) refers to the flow of component j from process k to process i.

\[\text{input}(i, j, t) = \text{raw}(i, j, t) + \sum_{k \neq i} \text{flow}(k, i, j, t) \quad (11)\]
\[\sum_j \text{raw}(i, j, t) \leq \text{supply}(j, t) \quad (12)\]

The stoichiometric relationship between each component is determined via the following equation using the coefficient \( f(i, j) \). The outputs are related using a similar equation.

\[\text{input}(i, j, t) = f(i, j) \sum_{j' \neq j} \text{input}(i, j', t) \quad (13)\]
\[\text{output}(i, j, t) = g(i, j) \sum_{j' \neq j} \text{output}(i, j', t) \quad (14)\]

A mass balance around each process is also specified. The sum of all inputs into the process must equal all the output.
\[ \sum_{i} \text{output}(i, j, t) = \sum_{i} \text{input}(i, j, t) \]  
\[ \text{output}(i, j, t) = \text{sales}(i, j, t) + \sum_{k \neq i} \text{flow}(i, k, j, t) \]

Another mass balance is performed for the output chemicals from each process. The flow variable is the same as defined previously, and the sales refer to chemicals that are sold on the market. Since a chemical may be produced by more than one process, a sum is taken over all the processes to determine the total production. To make sure the market does not become oversaturated with products, the sales must be less than the demand. The revenue may then be calculated by multiplying the sales of each product by their price.

\[ \sum_{i} \text{sales}(i, j, t) \leq \text{demand}(j, t) \]  
\[ \text{revenue}(j, t) = \text{price}(j, t) \cdot \sum_{i} \text{sales}(i, j, t) \]

There are also costs for each process that is related to the actual production. This accounts for maintenance, labor, and utilities. Similar to the fixed capital investment, there are two parts that are accounted for. There is a penalty that is incurred just for operating process and also an incremental cost related to the total output.

\[ \text{operatingcost}(i, t) = \delta(i) \cdot \sum_{t < t'} \text{Y}(i, t') + \epsilon(i) \cdot \sum_{j} \text{output}(i, j, t) \]

The summation of the binary variable \( Y(i,t) \) for all the previous time intervals prevents the penalty from being imposed until the process is built and also requires the penalty after it has been built.

The existence of central utilities is one of the advantages of having an integrated biorefinery. The utilities are shared among all the processes.

\[ \text{FCutilities}(u, t) = a(u) \cdot Z(u, t) + b(u) \cdot \text{utilitycapacity}(u, t) \]  
\[ \text{utilitycost}(u, t) = c(i) \cdot \sum_{t < t'} Z(u, t') + d(u) \cdot \sum_{i} \text{utilities}(i, u, t) \]  
\[ \text{utilityrequirements}(i, u, t) \leq \text{utilities}(i, u, t) \]  
\[ \sum_{i} \text{utilities}(i, u, t) \leq \text{utilitycapacity}(u, t) \]

\[ \text{utilitycapacity}(u, t) - Z(i, t) \cdot \text{maxutilitycapacity}(u) \leq 0 \]  
\[ \text{utilitycapacity}(u, t) - Z(i, t) \cdot \text{minutilitycapacity}(u) \geq 0 \]

Initially all of the operating costs are set to be zero. Assuming that each process costs zero to operate, some of the processes were still unprofitable and were therefore
eliminated. The only factors that are taken into account are the relative amount of input and output materials and their respective prices. In order to not exclude any profitable process, the investment limits and market demands are set to a very high amount. The result is that all the profitable processes are chosen without having to estimate any of the specific parameters. Raw materials are priced at 20% higher than the market price, to encourage the use of chemicals that are produced within our own refinery. As expected, the optimizer picks the most profitable processes to be constructed first.

Parameters

In order to accurately use the math model, the $\alpha, \beta, \epsilon$, and $\delta$ must be found from simulations of each process. Research was done on each process to find out what kind units are needed for each reaction process. After finding which simulations to run, and
running the simulations at different capacities, fixed capital and operating costs are graphed versus capacities. For the math model, $\alpha$ is the y-intercept and $\beta$ is the slope of the fixed capital versus capacity graph. $\epsilon$ is the slope and $\delta$ is the y-intercept of the operating costs versus the capacity graph. All of the specifics for the ethyl lactate process are described below as an example of how each process parameters were calculated.

**Ethyl Lactate**

Ethyl lactate has a wide variety of uses in industrial, commercial, and consumer applications. It is one of the lactate esters which act as a “green” solvent. It can be used as a degreaser in household products without the toxic chemicals. Ethyl lactate can be used to produce biodegradable plastics as well as industrial chemical products.

Ethanol and lactic acid are reacted in a CSTR to form water and ethyl lactate. Equimolar amounts of reactants form equimolar amounts of ethyl lactate and water with a 99% conversion of the reactants. Ethyl lactate is then separated from the water in a distillation column. The utilities and the FCI affect the profitability of the process and need to be taken into consideration when determining whether to include the process in the biorefinery.

![FCI vs. Feedrate](image-url)

Figure 5
Using a combination of PROII® and SuperPro® simulations the following parameters were determined and included the GAMS profitability model. The FCI was found to be linear between the feed rates of 2000 and 5000 kg/hr. The operating costs were linear throughout the simulations assuming that the man hours would be the same regardless of the size of the equipment. The utilities are determined by the mathematical model so those costs are not included at this point. The parameter $\beta$ which is the slope of FCI for this process was approximately 17.0 and the y-intercept $\alpha$ was $100,000. The parameter $\epsilon$ which is the slope of the operating cost for this process was 0 and the y-intercept was $283,875.$

![Operating Cost vs. Feedrate](image)

Figure 6

**Dilactide**

Dilactide is used to make high molecular weight polymers. These polymers are used in the manufacture of biodegradable plastics, plastic fibers, and extrusion coatings for cardboard. Dilactide is also used as a biodegradable drug delivery system in pharmaceuticals.

Lactic acid is reacted with a catalyst in a CSTR to form dilactide and water through a condensation reaction. Two lactic acid molecules form one dilactide and two water molecules. The catalyst is usually tin oxide or tin chloride however sulfuric acid can also be used. The reaction takes place at temperatures between 150 and 200°C this could make this process unprofitable due to the utility costs. The dilactide is separated from the
product stream through distillation. The equipment size and operating costs could be estimated however the simulations were beyond the scope of this project.

For the fermentations, FCI and operating costs were calculated using a simulation in SuperPro©. Picking an arbitrary reaction that will be used to base all of the fermentation parameters from, varying flow rates were imputed into the simulation. The operating costs were found on the itemized cost report. These results did not include the cost of the raw material; therefore, material costs were accounted for in the math model in GAMS. The fixed capital investment was also found in the itemized cost report. The graph that was produced from this information is shown below.

**Other Processes**

For all of the other processes that were not eliminated initially, fixed capital, operating costs, and utilities are estimated using careful techniques. In order to calculate these in a timely fashion, several assumptions are made.

Each process is defined as being run in either a CSTR, fermentor, PFR, distillation column, or any combination of the four. The four graphs for the operating costs and fixed capitals investments for the four types of units are shown in the following graphs. If for example one process required 2 reactors and a distillation column, the alphas and betas for 2 CSTRs and 1 distillation column are added together.

Figure 7
Figure 8

CSTR Operating Cost and FCI

Figure 9

Fermentor FCI and Operating Costs
The Fixed Capital Investment for the pieces of equipment are summed up in the above table for feed rates between 87,600 and 87,600,000 kg/year. This FCI accounts for the piping, electrical, installation, professional fees and other costs not typically associated with production costs.

Electricity required to operate the units are shown on figures 7, 8, and 9. On top of electricity, other process-specific utility costs are calculated based on the amount of heat that is needed or is released from each process, which is explained in more detail in the following section.

Utilities

To estimate the power plant investment and operating cost parameters, we consulted Plant Design and Economics for Chemical Engineers 5th Edition by Peters & Timmerhaus. Using the graph for steam generators, we could determine the purchased cost of steam based on capacity. We then took a linear portion of the graph to generate an equation relating purchased cost and capacity. This equation was used to determine the parameters $\alpha$ and $\beta$, which were the y-intercept and the slope, respectively. These parameters were implemented into the mathematical model to be used with the GAMS linear solver. A similar process was used for cooling towers to determine the purchased cost of cooling water in relation to capacity. The parameters for the cooling water utility function were also put in the mathematical model to be used with the GAMS linear solver.

Results
Five Million Dollar Investment

If the initial investment of the project is five million dollars, the model says to build eight processes. Not all processes are built in the first year, however. In the initial investment, only 2 processes are built, but after money that was made the first year is re-invested, the other processes are built. For the processes that are built in years 3 and 4, more of the revenue is needed before these processes are built; therefore, they must wait a couple years after the beginning of the project. The net present value for the five million dollar investment is around 28 million dollars.

\[ \text{NPV} = 27,931,290 \]

Expansions are done as early as possible because the more of each product produced, the more profitable the investment. Constraints are specified in the model for the frequency that each process can expand. The specifications say that one process may not expand until 3 years after it is built, and may only expand every three years. Most processes have the option to expand in years 9 and 10; however, they are not picked to expand. This is because if built, they would only utilize the expanded capacity for years 9 and 10 and a return would not be made on the investment.
For the five million dollar investment, the operating costs for every year are almost half of the amount of revenues that come in. Utilities, operating costs, and raw materials for one year are included in the costs. The profits for each year are the difference between the two lines.
The above graph compares the amount of cash available for each year to the amount that is re-invested each year. The cash line shown above is the profits minus the investments. As you can see, in the first five years of the project, much more money is being invested, and this number decreases throughout the life of the project. The cash, in contrast, starts out at 5 million, decreases after the initial investment is made (fixed capital) and slowly increases from there as we begin to make more money from the revenue.

![Figure 12](image)

Around year 4, there’s been enough money made to pay back the loan and any additional revenues are pure profit. This point is otherwise known as the break-even point.
Twenty Million Dollar Investment

The twenty million dollar investment option chooses to build three processes for each of the first two years. After the third year, no more new processes are built. Overall, this investment turns out to be the less profitable than the five million dollar investment.

NPW: $24,545,680

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Table 4

The break-even point is not reached until the fifth year. The cumulative cash reaches barely above 50 million dollars, as opposed to the other investment options that are well over 50 million dollars.

Figure 13
The cash vs. re-investment graph for this option is interesting as well. The cash available drops to near zero at year 2, but then never reaches above the initial investment point, which is 20 million dollars. This investment is too high, and would not be deemed profitable.
The costs vs. revenue graph does not differ from the previous results. This does not consider the initial investment.

Variable Investment

From the previous results, it is apparent that the choice of investment has an effect on the NPW of the biorefinery. The optimization may be expanded to include the choice of investment by declaring it as a variable in the mathematical model. The net present worth is higher in this case because we only borrow the exact amount that we want to spend; in this case we incur less interest charges from our loan. If we borrow more money than we need, we will be sitting on the money, and will eventually end up paying interest for money that was not needed.

Three processes are built in the first year, three in the second, one in the third, and one in the forth. As there is more money to spend, more processes are built. This option builds processes later in the lifetime of the project than the other options. The optimal amount of money was invested; therefore, there is an optimal amount of money to re-invest to build more processes.

NPV = $28,800,000
Investment = $7,535,352
With the variable investment, the revenues are also double that of the costs, as shown above.
The cash vs. re-investment for this option shows interesting results. The entire investment is not used in the first year of the project. A portion of the investment is saved to use in the following years.

![Figure 18](image)

The cumulative cash at the end of the project is shown to be about 58 million dollars.

![Figure 19](image)
As the graph shows, the comparison of the three different investments, 5 million, 7 million, and 20 million, shows how the model picks the best choice of investment options. The twenty million dollar investment is the worst investment, five million is somewhat better, and the seven million dollar investment is obviously the best choice.

Non-Integrated Processes: Variable Investment

For the non-integrated process option, the net present value is around 24 million dollars. This is, as expected, the least profitable option. In order to run this model, it is specified that none of the outputs from the processes are allowed to be inputs of another process. Therefore, every process has to buy raw materials from the market. The difference in NPV’s for the non-integrated processes and the integrated processes would be even greater if the utilities were separated rather than integrated because the fixed capital investment would be much higher. Also, the amount of money spent on purchasing the land for an integrated biorefinery is much smaller than if you had to purchase land at several different locations. This also makes an integrated biorefinery a better choice.

As you can see in this option only three processes were built. This is because since the processes are not able to share their chemical intermediates, it is not profitable to build more processes.

Initial Investment: $5,538,928
NPW: $24,141,340

The following graph is a comparison of the integrated processes versus the non-integrated processes. Each process is not allowed to share chemical intermediates. Each must be bought from the market. The amount of money that is made at the end of the life of the project is much greater for the integrated process.
Increasing Prices

If the prices that we sell our products for were to increase by five percent each year, the following results are given from the model. The model picks much more of the processes to be built, and expansions are done in the last year for this case as well.

NPW: $83,656,330
Investment: $12,925,130
Figure 21

Figure 22
Changing Demand

The demand of the processes is another parameter which had to be put into the math model. Demand can drastically change the results that the model will give us. If the demand changes, the amount of money made can drastically change, making demand one of the most important parameters.

One of the most demanded chemicals that can be produced in a biorefinery is ethanol. The largest demand for ethanol in the near future will be for alternate fuel sources. As the industry produces more of the chemical, and the price to buy ethanol decreases by as much as 60 cents, ethanol will be one of the leading fuels. [5] Ethanol can also be used as a solvent and in cosmetics, toiletries, coatings, detergents, cleaners, pharmaceuticals, and intermediates. [9]

Glycerin, which is a byproduct of biodiesel production, has a large market as well. Glycerin can be used in medical and pharmaceutical preparations, lubricants, laxatives, cough syrups, and elixirs. Glycerol can also be used in personal care items such as hair products and is also put into food and beverages [2].

Acetic acid, or ethanoic acid, is another chemical that can be produced from biomass. “Acetic acid is an organic chemical compound best recognized for giving vinegar its sour taste and pungent smell.” [9] It is produced through fermentation, like many of the chemicals that are being considered. The world demands of some of the chemicals that are in our projected product tree are listed in the table below.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Demand (million pounds)</th>
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<tbody>
<tr>
<td>Methanol</td>
<td>1.24E+09</td>
</tr>
<tr>
<td>Levulinic acid</td>
<td>1.00E+00</td>
</tr>
<tr>
<td>Acetic Acid</td>
<td>6.10E+03</td>
</tr>
<tr>
<td>Ethanol</td>
<td>1.32E+08</td>
</tr>
<tr>
<td>Acrylic Acid</td>
<td>6.40E+03</td>
</tr>
<tr>
<td>Succinic Acid</td>
<td>5.40E+02</td>
</tr>
</tbody>
</table>

Changing Demand

The model of the biorefinery was tested under different market conditions. For the first study, the demand of each product increases each year. The maximum capacity of each process is less than the specified demand for each product that is profitable. When the demand increases each year, each process is built at maximum capacity and has the maximum expansion each year. Only the processes previously mentioned are involved in this case study. More interesting results occur when the demand decreases over the lifetime of the biorefinery.

The second study is of decreasing demand over the project lifetime. Each chemical component starts at the current market demand and decreases substantially over the lifetime. The expansion procedure is examined under these changing conditions. The
investment limit is set at 50 million dollars. The construction and expansion of each process is shown below.

The other processes are operating at maximum capacity throughout their lifetime until expansion stops. At this point, the demand has decreased past sales and operating at capacity is unprofitable. It is interesting to note that some processes, which were previously unprofitable, are now being built. Since it is not possible to sell all of the products from other processes, it is necessary to send them somewhere. The optimal solution includes building an unprofitable process to dispose of any products that cannot be sold reducing the cost of waste treatment or disposal.

**Problems and Goals**

One of the main objectives for the next portion of this project is to decide upon a feedstock or feedstocks for the biorefinery. There are many different feedstocks that can produce all of the components that are in the projected product tree. Many crops can be used, or portions of crops, as input for the refinery. A whole-crop biorefinery uses the entire crop to produce several different products. For example, corn crops can be used in a whole crop biorefinery where the actual corn and the corn stover are used and processed. Other biorefineries just use the corn and the corn stover is thrown away as waste. “A green biorefinery is a multi-product system which handles its refinery cuts, product, and fractions in accordance with the physiology of the corresponding plant material.”[3] Green biorefineries use only unprocessed, natural crops and chemicals as biomass feedstock. Lignocellulosic feedstock biorefineries are also another option. This kind of refinery consists of polymers, cellulose and lignin and “uses hard fibrous plant materials generated by lumber or municipal wastes.”[3] There a vast range of feedstock choices, and choosing a feedstock can be quite a challenge.

Location of the biorefinery will be put into our mathematical model as a variable. The cost of land in different locations can vary greatly; therefore, the location of the refinery will greatly affect the Net Present Value of the refinery because the fixed capital investment will decrease or increase based on that. Transportation of feedstock must be accounted for. Therefore, the farther away the plant is from the production of feedstock, the more the operating costs will be. This is a decision that will be made before the final cost breakdown can be done.

The mathematical model produced does not account for the uncertainty of product demand in the market. The change in demand of products is common in industries, and must be accounted for in our model.
References

4. [http://www.umich.edu/~gs265/society/fossilfuels.htm](http://www.umich.edu/~gs265/society/fossilfuels.htm)