A DECISION SUPPORT SYSTEM FOR BIOREFINERY LOCATION & LOGISTICS

Except where reference is made to the work of others, the work described in this thesis is my own or was done in collaboration with my advisory committee. This thesis does not include proprietary or classified information.

Sujith Sukumaran

Certificate of Approval:

Harry T. Cullinan Professor Chemical Engineering	Kevin R. Gue, Chair Associate Professor Industrial and Systems Engineering
Robert Bulfin Technology Management Professor Industrial and Systems Engineering	Burak Aksoy Research Fellow III Chemical Engineering

George T. Flowers
Dean
Graduate School

A decision support system for biorefinery location & logistics

Sujith Sukumaran

A Thesis

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Master of Science

Auburn, Alabama
August 10, 2009

A DECISION SUPPORT SYSTEM FOR BIOREFINERY LOCATION & LOGISTICS

Sujith Sukumaran

Signature of Author

Date of Graduation

VITA

Sujith Sukumaran, son of Sukumaran and Geethabai, was born on May 26th, 1985, in Coimbatore, India. He graduated from Ramnagar Suburban Matriculation Higher Secondary School in 2002. He attended Sri Krishna College of Engineering and Technology, affiliated to Anna University, Coimbatore, where he earned his Bachelor of Engineering Degree in Mechanical Engineering in 2006. He then enrolled in the Graduate School at Auburn University, Department of Industrial and Systems Engineering, in January 2007.

THESIS ABSTRACT

A DECISION SUPPORT SYSTEM FOR BIOREFINERY LOCATION & LOGISTICS

Sujith Sukumaran

Master of Science, August 10, 2009
(B.E., Anna University, 2006)

87 Typed Pages

Directed by Kevin Gue

The use of forest biomass, a renewable resource, as a source of fuels or chemicals is hindered by logistics. Economic success of the bioenergy concepts and their products may also depend on the solution to the logistics problem. A decision support system (DSS) has been developed to identify locations for biorefineries in the state of Alabama. The DSS is comprised of two models, a location and an economic model. In the location model, biorefinery location and the catchment area for the biomass are identified in such a way that it will incur the least transportation cost. It also selects the type and number of equipment needed for the first three stages of the supply chain such as loading, transport from forest site to road site and preprocessing. In the economic model, the DSS uses the cost outputs from the location model and cost inputs from the user to calculate the investment and the rate of return on investment. The user has initially to choose from a list of biomass conversion technologies which are to be used in the biorefinery. The DSS supports decision makers in analyzing the biomass supply, estimating the profitability of investments, and evaluating necessary investments in infrastructure and equipment for biorefineries.

ACKNOWLEDGMENTS

Firstly, I offer my sincerest gratitude to my advisor, Dr. Kevin Gue, who has supported me throughout my thesis with his patience and knowledge whilst allowing me the room to work in my own way. I attribute the level of my Masters degree to his encouragement and efforts and without him this thesis, too, would not have been completed or written. I also wish to thank Dr. Burak Aksoy who has taught me all the basics of the biorefinery process. His recommendations and suggestions from the preliminary to the concluding level have been invaluable for the development of the project and for software improvement. I would like to thank Dr. Harry Cullinan and Dr. Robert Bulfin for their invaluable help during this study and for serving on my committee. Thanks also to Dr. Muehlenfeld of the School of Forestry and Wildlife Sciences for assistance in describing the practical aspects of biomass transportation. Finally, I would like to thank my family and friends for all their support and understanding without which I could have never completed this program.

Style manual or journal used Latex: A Document Preparation System : User's Guide and Reference Manual, by Leslie Lamport (together with the style known as "aums").

Computer software used to build this decision support system is Microsoft Excel 2007. The decision support system contains a written document, software and a user's manual. To get a copy of the decision support system, contact Dr. Kevin Gue

TABLE OF CONTENTS

List of Figures

Chapter 1

Introduction

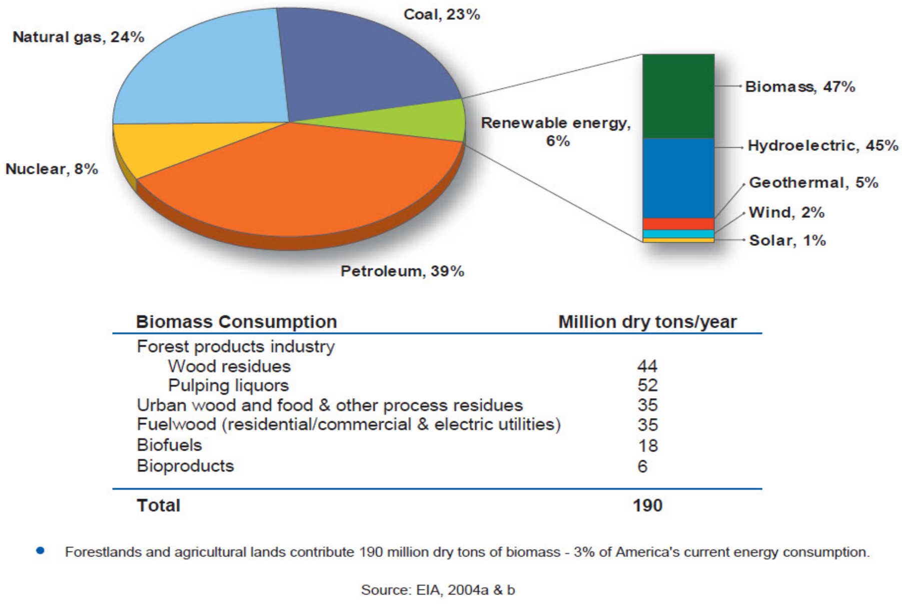
1.1 Background

Global energy demand is expected to grow at 1.3% per year on average until 2030 (The outlook for energy, 2007). This increase will be due to economic and population growth. At the same time, significant energy efficiency gains will help us to balance overall demand increases. The United States economy depends on the continuous availability of low cost energy. This dependence on lower cost energy has assumed increased significance in the current economic and political environment. More than 85% of energy consumed in 2005 in the United States was from fossil fuels, namely coal, petroleum, and natural gas. Less than 7% of energy was from renewable resources, of which, alcohol fuels was a mere 0.4% (Department of Energy, 2006). In 2008, the United States consumed 20.68 million barrels of petroleum products per day (about 7.5 billion barrels per year). Roughly 58% (4.35 billion barrels) of petroleum consumed was imported, with about 13% ($\sim$ 0.9 billion barrels) coming from Persian Gulf countries (Annual energy outlook, 2006).

The widespread use of fossil fuels and the resulting release of greenhouse gasses have been blamed for global warming, increasing sea levels and changing climatic patterns. This has led to a renewed global interest in fuels from biological sources, primarily because they are usually net zero contributors to greenhouse gasses.

1.2 Biomass as a renewable energy

Renewable energy is the energy generated from natural resources which are renewable, or naturally replenished, such as solar, wind, hydro and biomass. According to National Renewable Energy Laboratory, biomass is defined as any plant-derived organic matter which includes herbaceous and woody energy crops, agricultural food and feed crops, agricultural crop wastes and residues, wood wastes and residues, aquatic plants, and other waste materials including some municipal wastes. Also woody biomass is defined as/: “the trees and woody plants, including limbs, tops, needles, leaves, and other woody parts, grown in a forest, woodland, or rangeland environment, that are the by-products of restoration and hazardous fuel reduction treatments” (U.S.Department of Agriculture, Department of Energy, and Department of the Interior, 2003). Biofuels are liquid, solid, or gaseous fuels derived from renewable biological sources and can be burned directly for thermal energy or converted to other high-value energy sources including ethanol, biodiesel, methanol, hydrogen, or methane. There is a history of biomass being used as fuel for thousands of years and it is today a major fuel used worldwide. Biomass is also the only alternative way to obtain liquid fuels that are used today compared to other forms of renewable energy. Figure 1.1 shows the present state of renewable energy used in the United States, with renewable energy representing only 6% of the total, and biomass representing a little above 2.5%. In an effort to push forward greater utilization of renewable energy, the federal government through the Department of Energy has put forth benchmark biomass initiative goals for 2020 which are to have 5% of all power, 10% of all fuels, and 18% of all bioproducts being supplied by biomass and serving as replacements for what otherwise would be fossil fuel expenditures (DOE, 2002).



Biomass Consumption	Million dry tons/year
Forest products industry	
Wood residues	44
Pulping liquors	52
Urban wood and food & other process residues	35
Fuelwood (residential/commercial & electric utilities)	35
Biofuels	18
Bioproducts	6
Total	**190**

- Forestlands and agricultural lands contribute 190 million dry tons of biomass - 3% of America's current energy consumption.

Source: EIA, 2004a & b

Figure 1.1: Summary of Energy Consumption

Allen et al. (1998) has categorized biomass fuels into four groups:

1. Wood (such as forest fuel available after felling of trees, thinning of forests),
2. Crop residues,
3. Dedicated energy crops grown specifically to be used as fuel, and
4. Urban wastes (human and animal excretement).

There are refinery technologies to convert any type of biomass to energy. According to Allen et al. (1998), primary biomass fuels can be used directly or can be converted into secondary fuels such as liquid or gaseous fuels through the use of various technologies. In our research we have concentrated on woody biomass.

1.3 Economics of a biorefinery

The major constraint to the use of biomass fuels in the U.S. is economics— the cost of producing biofuels is higher than that of the wholesale price of fossil fuels. Biofuels competitiveness depends on the wholesale price of the fossil fuels. Researchers are trying to develop an understanding of the economics of the biorefinery processing because it is crucial in realizing eventual commercialization.

Constructing and operating a new biorefinery requires a commitment of large amount of money. The decision to make such a commitment is based upon many factors, one of which is the prices of the products obtained from the biorefinery. Apart from product prices, other factors influencing the decision making process are installation cost, operating costs, supply chain costs, market position, health, safety and environmental concerns. Biorefineries require a large capital investment even before it can be put into operation. The various costs estimates associated with erecting and operating a biorefinery are as follows: capital investment, raw material costs, supply chain costs, labor costs, overhead costs and general expenses. Revenue for the biorefinery comes from sale of the products produced by the plant. These estimates become the data for evaluating the economical consequences of the project. Rate of return on investment is used as a measure of estimating profitability in the economic analyzes.

1.4 Biomass supply chain

The steps which control the biomass supply chain are as follows:

1. Harvesting the feedstock in the field or forest.
2. Handling and transporting the biomass from the field to a point where road transport vehicles can be used (First stage transport).
3. Storage of biomass; Biomass is harvested at specific times of the year hence it is to be stored to ensure a year-round supply to the biorefinery.
4. Preprocessing; This is generally done to improve the handling efficiency and quantity during transport.

5. Transportation; to transport the fuel from the collection site to the biorefinery (Second stage transport).

Among these, transportation has been identified as one of the largest cost contributors to the cost of biomass feedstock (Hess et al., 2007; Allen et al., 1998; Bhat et al., 1992; Kumar et al., 2004). The logistics of biomass fuel supply are complex and problematic, and logistics costs will have an important bearing on the total delivered cost of biomass (i.e. the total cumulative cost of biomass fuel at the point of delivery to a power station). For example, the economic competitiveness of cellulosic ethanol production is highly dependent on feedstock cost, which constitutes 35-50% of the total ethanol production cost, depending on various geographical factors and the types of systems used for harvesting, collecting, preprocessing, transporting, and handling the material (Hess et al., 2007). The logistics associated with moving the biomass from the land to the biorefinery can make up 50-75% of those feedstock costs, however, logistical costs exceeding 25% of the total biomass value leave very little profit margin for biomass producers and biorefinery operators (Hess et al., 2007).

Sokhansanj et al. (2006) provides a few factors which they believe are most important while designing a supply chain for biorefinery:

- The maximum rate of biomass supply to biorefinery,
- Form and bulk density of biomass,
- The distance biomass has to travel to reach to biorefinery, and
- Transportation infrastructure available between the points of harvest and biorefinery.

Biomass has lower energy density and physical density than other fossil fuels. Fiedler et al. (2007) have classified the operations taking place during preprocessing. These operations influence the attributes of the transported, stored and utilized biomass products. The low bulk density of most biomass fuels reduces the tonnage capacity of trucks, resulting in larger truck movements. Mani et al. (2006) has shown that the pelletizing operation increases the bulk density of the biomass and also improves the ease of transportation. Each of these factors are responsible for high transportation and logistics costs in biomass supply.

Because transportation is one of the major costs involved in the economics of biorefinery, we can say that it partially determines the feasibility of biorefinery in the state. A reduction in transportation cost considerably increases the profitability of the investment which, in turn, increases the rate of return on investment. Transportation cost can be minimized by optimizing the location of the biorefinery.

1.5 Research questions

The most important question we are trying to answer with this research is, "Can a biorefinery be located profitably in the state of Alabama?", other questions are:

- Where will the biorefinery be located in the state?
- What is the region of supply to the biorefinery?
- How much of feedstock is supplied by each of the counties in the supply region?
- What is the transportation cost incurred?
- How much capital investment is required for the biorefinery?
- What is the estimated rate of return on investment?

1.6 Thesis organization

The decision support system has two parts, a facility location model and a model for economic analysis. The facility location model is first explained, followed by the economic analysis and then how they both are integrated in Excel. We also perform some experiments using the decision support system to examine the effects on prices of various products and technologies. The use of these sensitivity analyzes, although restricted in scope, provides a framework for evaluating future development and identifying critical areas that need to be addressed before commercial success can be assured. With a focused study, different component designs can be evaluated, the performance of the system responses can be observed and economic impact assessed. Though this thesis is devoted to the single state of Alabama, the framework and the concepts developed should be transferable to any other state of similar or lesser size and readapted for newer environment and management policies.

Chapter 2

Facility Location Model

Facility location problems are a special case of optimization problems solved by operation researchers. The objective of the problem is to locate a facility with "Minimal Cost" while satisfying all the constraints. There are many ways of classifying the location models. Daskin (2008) has classified location modeling into four types: analytical, continuous, network, and discrete. Daskin (2008) further classified discrete location models into three broad areas: covering based models (set covering, maximum covering, p-center), median based model (p-median, fixed charge) and other models.

In covering based models, the objective is to cover critical distance or time and demands within them and to be served in order to count them as 'covered'. Examples include locating fire stations, emergency vehicles bases, and so on. For a set covering model, the objective is to cover all the demand points with a minimum number of facilities. In the maximum covering model, the objective is to cover maximum demand with a fixed number of facilities. In the p-center model, we seek the smallest possible coverage distance so that every node is covered.

In median based models, the objective is to minimize the demand-weighted distance between the facility and the demand nodes. Such models are widely used in distribution planning. For the p-median model, the objective is to minimize the average distance between demands and the nearest p sites. An uncapacitated fixed charge model is an extension of the p-median problem with capacities on facilities. Our problem is similar to the p-median problem.

2.1 Data sources for the model

2.1.1 Forest resources

Alabama has rich forest resources and is home to many companies in the pulp and paper industries. The processing of forest resources in these industries generates a significant amount of biomass. These secondary forest residues constitute the major portion of the biomass that is in use today. Muehlenfeld (2003) reports the total forest resources available in the state of Alabama. We use this data in our model for determining the facility location and supply counties. Muehlenfeld (2003) categorizes the woody biomass available in the state of Alabama into three categories: standing woody biomass, forest residues, and manufacturing residues. Each category includes different types of wood, which have their own attributes and challenges. It is important to know the maximum volume of biomass available to us to determine the location of biorefineries.

In our decision support system we have incorporated all woody biomass available except for the standing woody biomass. Standing forest biomass inventory is defined as the dry weight of all wood and bark above a one-foot stump in all live trees that are 1 inch or greater in diameter at breast height and located on commercial forest land (Muehlenfeld, 2003). This volume of biomass is generally not available for biorefinery use because it is used for production in the pulp and paper industries. Hence, the other two categories (forest residues and manufacturing residues) are the actual fuel available for use in a biorefinery.

Forest residues

Forest residues constitute both the logging residues and cull trees. Logging residues are the potential leftovers from harvesting operations, such as crowns, limbs and unused portions of growing stock trees. In Alabama, approximately 2.6 million oven-dry tons of logging residues can be recovered annually. Logging residues can be easily obtained using whole tree chipping operations. The operations produce “dirty chips” whose economics are well understood in practice (Muehlenfeld, 2003). Throughout our model, we assume that the refinery uses feedstock in the form chips. Another source of forest residues is the cull, or rough trees, which are the trees that do not have any value other than their potential as biomass fuel. It is estimated that there are approximately 2.7 million dry tons available annually in Alabama. Figure 2.1 displays the distribution of forest residues in Alabama available annually.

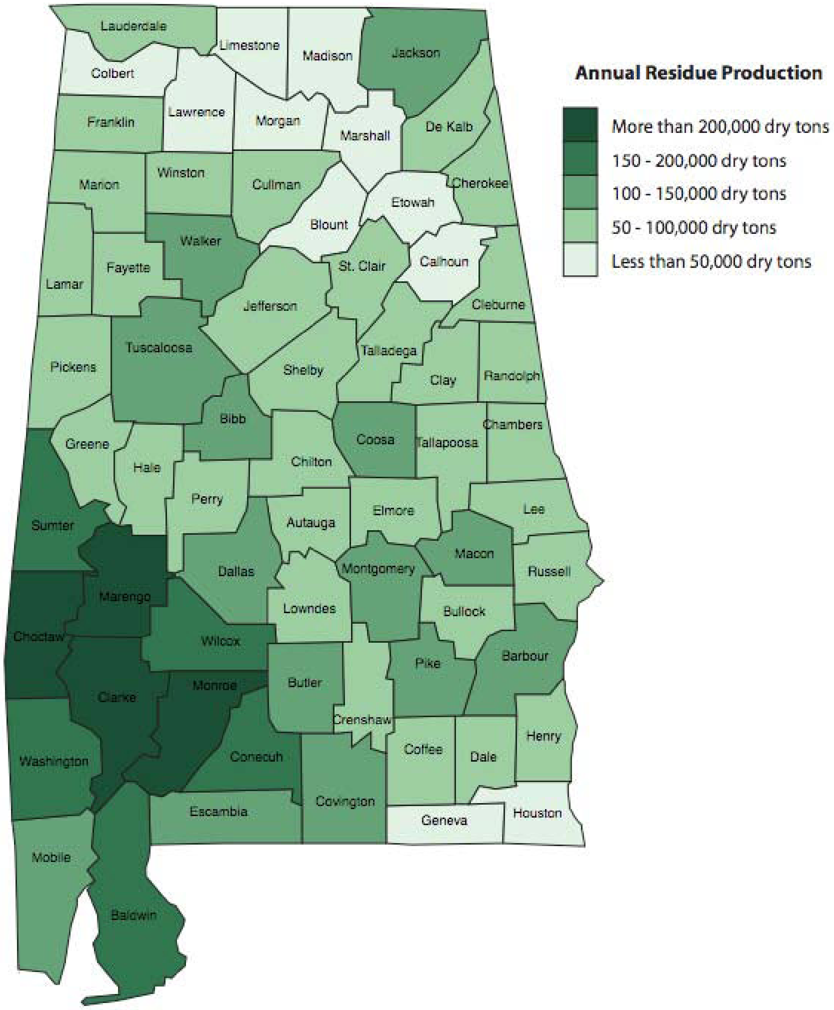


Figure 2.1: Total forest residues available in Alabama (Muehlenfeld, 2003)

Manufacturing residues

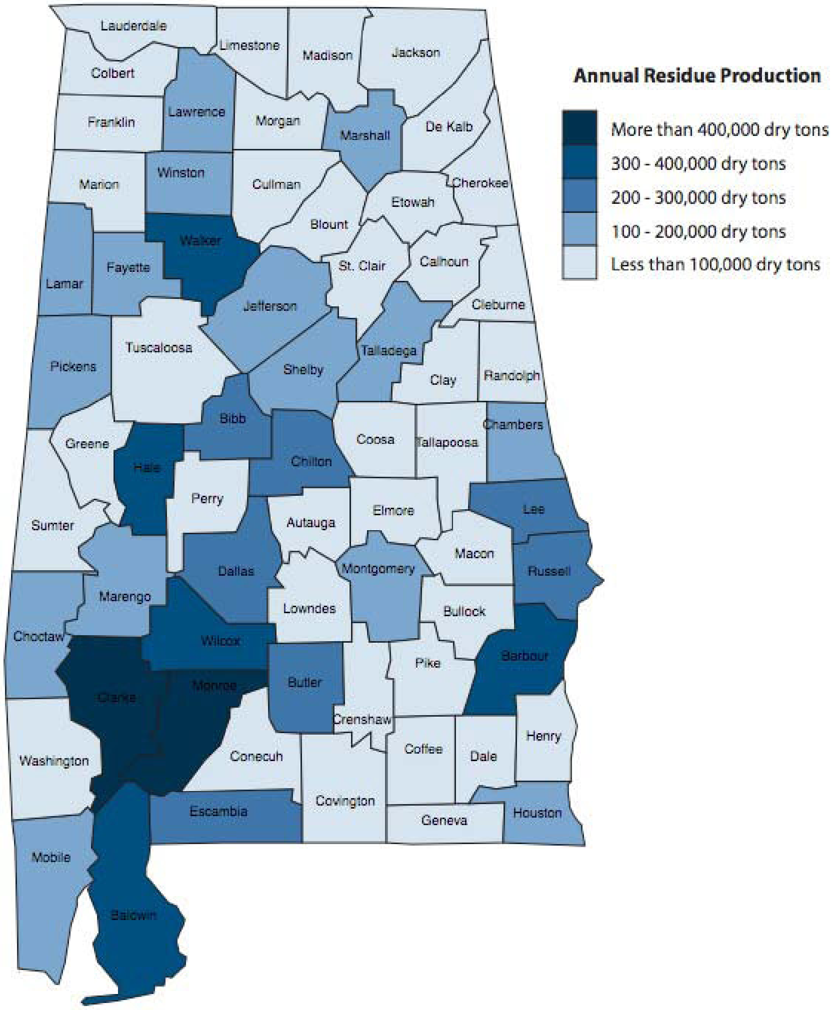


Figure 2.2: Total mill residues available in Alabama (Muehlenfeld, 2003)

Forest industries are categorized into two sectors, primary manufacturing and secondary manufacturing. Primary manufacturing sectors use wood coming from the forest directly for operations. Secondary manufacturing sectors use products from the primary sector as raw materials and adds value to it. Both the sectors produce waste materials which have potential for use as fuel in a biorefinery. According to the Alabama forestry commission, 99% of the primary manufacturing residuals are used for other purposes like fuel, fiber for pulp etc., but the availability of these residuals for the biorefinery greatly depends on the economics. Even though secondary manufacturing residues are comparatively of lesser volume than primary residuals, it is estimated that Alabama produces slightly more than one-half million oven-dry tons per year. Figure 2.2 displays the distribution of manufacturing residues in Alabama available annually.

2.2 Assumptions

We assume that the locations from which the feedstock are taken are the centroids of the particular counties. The distance matrix d_{ij} is obtained by calculating the round trip distance between centroids of counties. The actual road distances between the centroids were obtained using Google Earth. The model also assumes that the same cost is involved in transporting all types of feedstock which is not the case practically. The mode of transport for the second stage of transportation is assumed to be trucks.

2.3 Model

We define the following notation:

Indices

- i, j – Indices denoting locations – i is the refinery location, j is the counties of raw material procurement.

Decision Variables

- x_i– Equals 1 if a factory is located in county i and 0 otherwise.
- y_{ij}– Proportion of feedstock available in county j used for the refinery in county i.

Parameters

1. a_j – Availability of forest residues in county j in dry tons.
2. b_j – Availability of mill residues in county j in dry tons.
3. R – Requirement for feedstock in the refinery in dry tons.
4. p – Number of facilities to be located.
5. n – Number of counties (67 for Alabama).
6. C_f – Cost per ton for the first three stages of the biomass supply chain in \$/ton.
7. C_{ij} – Transportation cost to move feedstock from county j to refinery in county i in \$/ton-mile.
8. d_{ij} – Centroid distance between county j and county i in miles.
9. β_f – Percentage of forest residues in county that can be used as a feedstock for refinery.
10. β_m – Percentage of mill residues in county that can be used as a feedstock for refinery.

Our objective is to

$$\text{Minimize} \sum_{i=1}^{n}\sum_{j=1}^{n} [\beta_f a_j + \beta_m b_j]\, C_{ij}\, d_{ij}\, y_{ij}$$

Subject to

$$\sum_{j=1}^{n} [\beta_f a_j + \beta_m b_j]\, y_{ij} \geq R\, x_i \forall i \tag{2.1}$$

$$\sum_{i=1}^{n} x_i = p \forall i \tag{2.2}$$

$$\sum_{i=1}^{n} y_{ij} \leq 1 \forall j \tag{2.3}$$

$$0 \leq y_{ij} \leq 1 \forall i, j \tag{2.4}$$

$$x_i \in \{0, 1\} \forall i \tag{2.5}$$

The objective is to minimize the total variable cost of transportation. Constraint set 2.1 ensures feedstock requirements are met at the biorefineries. Constraint set 2.2 requires the number of facilities to be located to be equal to p. Constraint set 2.3 ensures no county provides more than its available supply.

The model developed here is a mixed integer problem which is complex to solve. The difficulty arises from the fact that integer programming problems have many local optima and finding a global optimum to the problem requires one to prove that a particular solution dominates all feasible points. Premium solver 8.0 developed by Frontline systems is capable of solving mixed integer problems and is also compatible with Microsoft Excel. Hence, we build the decision support system in this widely used application, Microsoft Excel 2007, with addin Premium solver 8.0.

We applied this model to the state of Alabama. We calculated the density of biomass available in each of the counties of the state. We obtained the ten richest counties in terms of density of biomass available for use in the biorefinery and plotted them in a map as shown in Figure 2.3. As we can see in the Figure, the biomass rich counties are located in some counties in the center, in the southwest and central east of the state. Intuitively, we would predict the biorefineries to be located somewhere close to these areas.

For example, to find out how the model behaves, we tried to locate a biorefinery of the capacity of 550 tons/day. We also assumed that the percentage of forest and mill residues (β's) available from each of the counties to be 60%. The results of the model point to Chilton county as the optimal site for locating this biorefinery. The results also indicate that the refinery uses 66% of the total biomass resources available from Chilton county, and none from surrounding counties. We can see from Figure 2.3 of the density plot that Chilton is among the top ten biomass rich counties in Alabama. The results from the model are plotted in Figure 2.4.

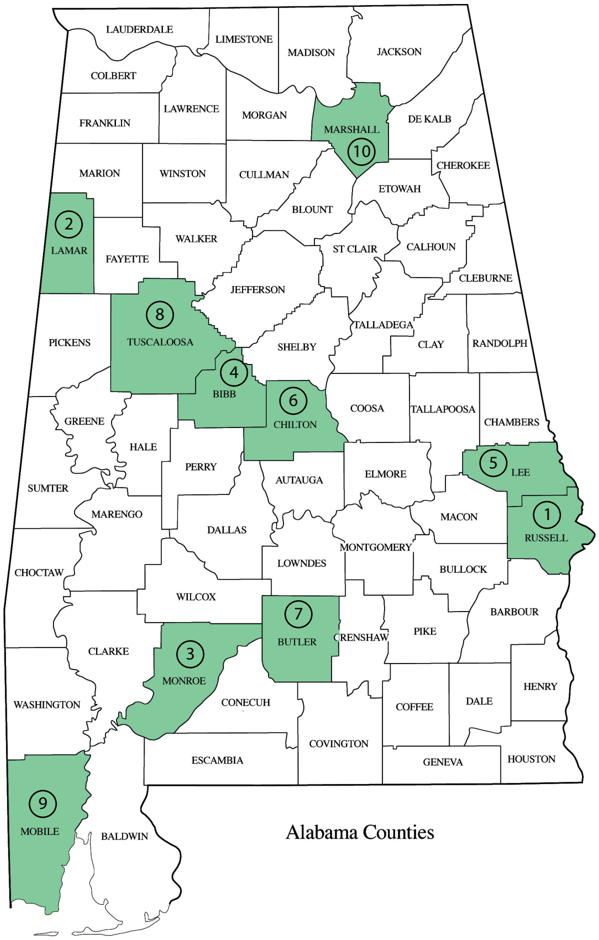


Figure 2.3: ten biomass rich counties in Alabama.

With the same set of inputs, we increased the number of refineries to 2. The result of the model points to the optimal locations of Lamar and Russell counties. The refinery located in Lamar county uses 100% of its available biomass and also 24% of the biomass available from Fayette county. The refinery located in Russell county uses 96% of the total biomass available from itself. Both Lamar and Russell counties are among the top ten

Figure 2.4: Results for p = 1

biomass dense counties in Alabama. Another important point to note in the result is, how the model tries to spread the facility locations over different parts of the state in order to make use of the biomass potential available in those areas rather than concentrating it to one part of the state. Figure 2.5 shows the results of the model.

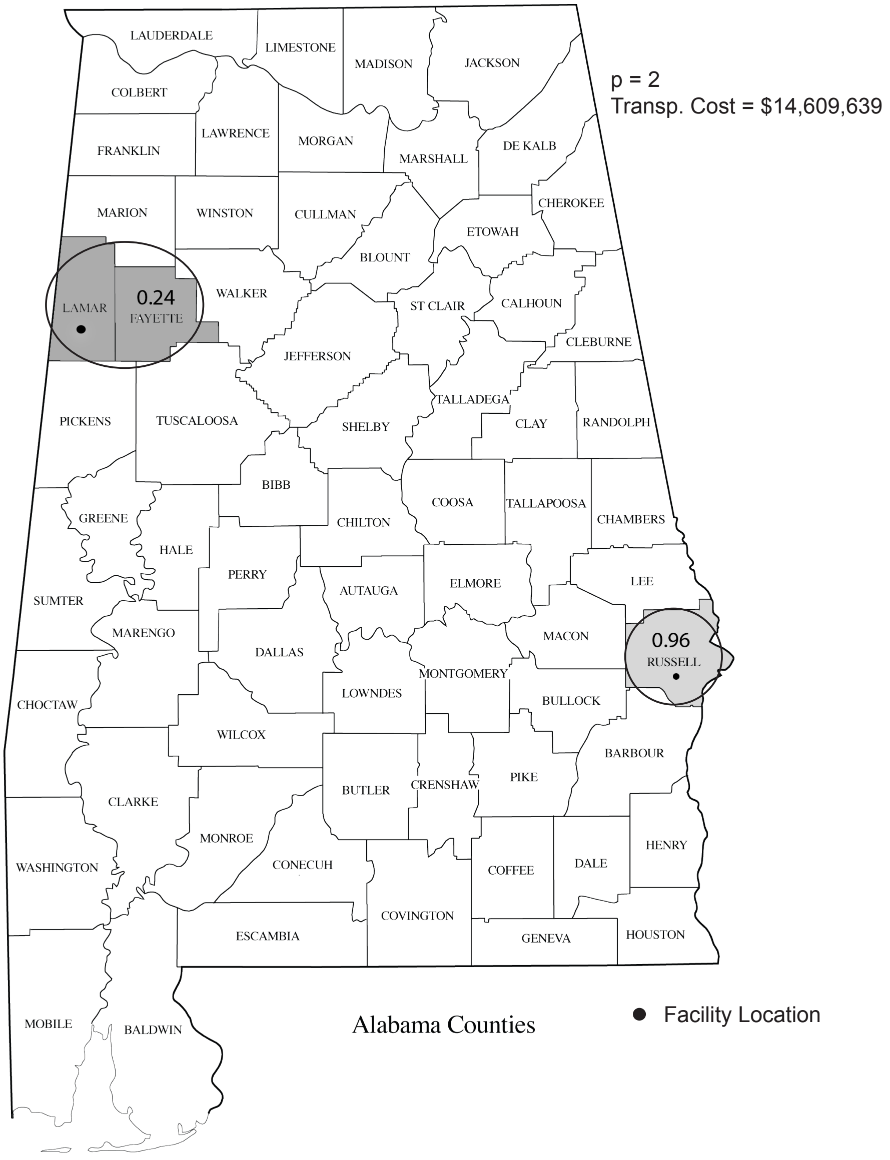


Figure 2.5: Results for p = 2

For p value equal to 3, the model chose Bibb, Lamar and Russell counties as optimal facility locations. The results follow the same pattern as the previous experiments. Figure 2.6 shows the optimal locations and the regions of supply for the refineries.

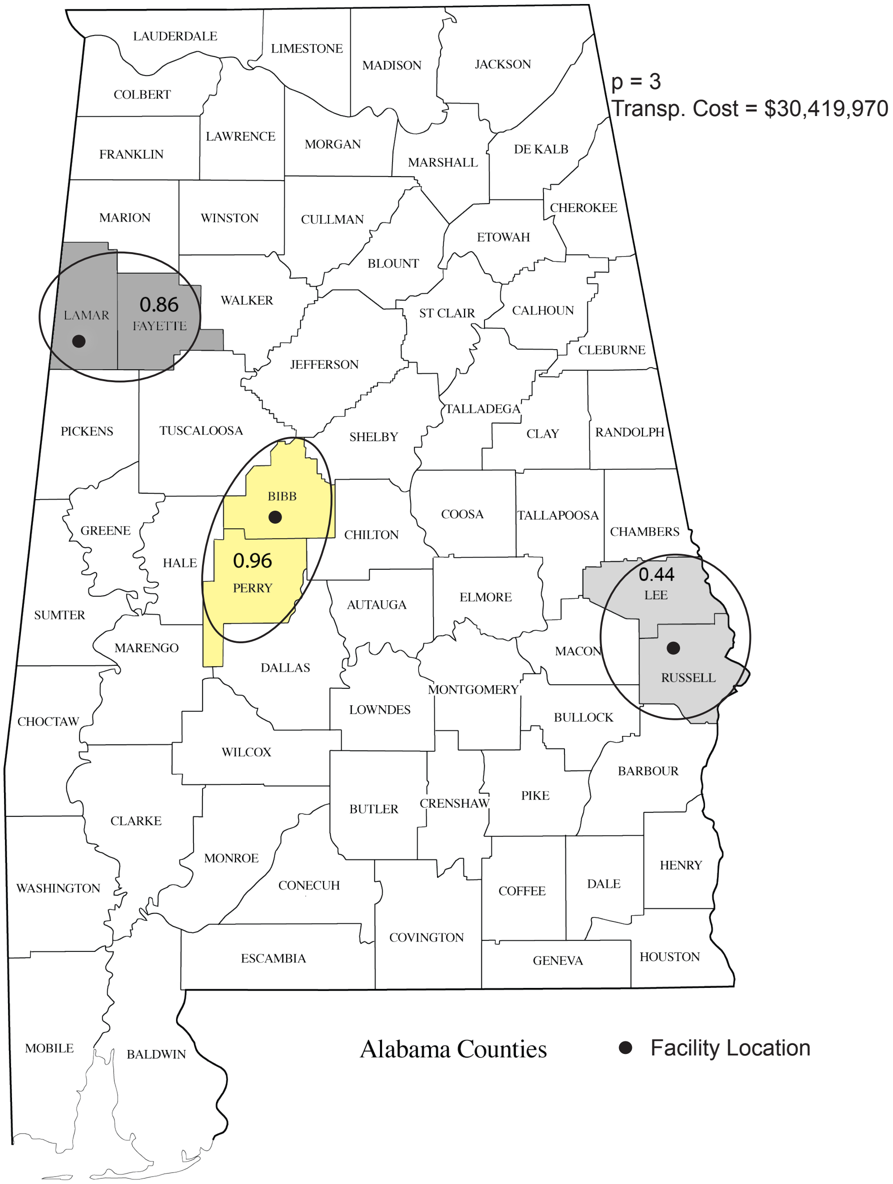


Figure 2.6: Results for p = 3

For p value equal to 4, the optimal locations identified by the model are Butler, Lamar, Monroe and Russell counties. The refinery located in Lamar county uses 100% of its available biomass and also 24% of the biomass available from Fayette county. The refinery located in Russell county uses total biomass available within it and also 91% of the biomass available from Lee county. The refinery located in Butler uses 100% of its available resource and also gets the biomass supply from Crenshaw and Conecuh counties. 46% of the biomass supply from Conecuh county goes to the refinery located in Butler county and the rest goes to the refinery located in Monroe. The refinery located in Monroe county also gets 2% of the total biomass available from Clarke county.

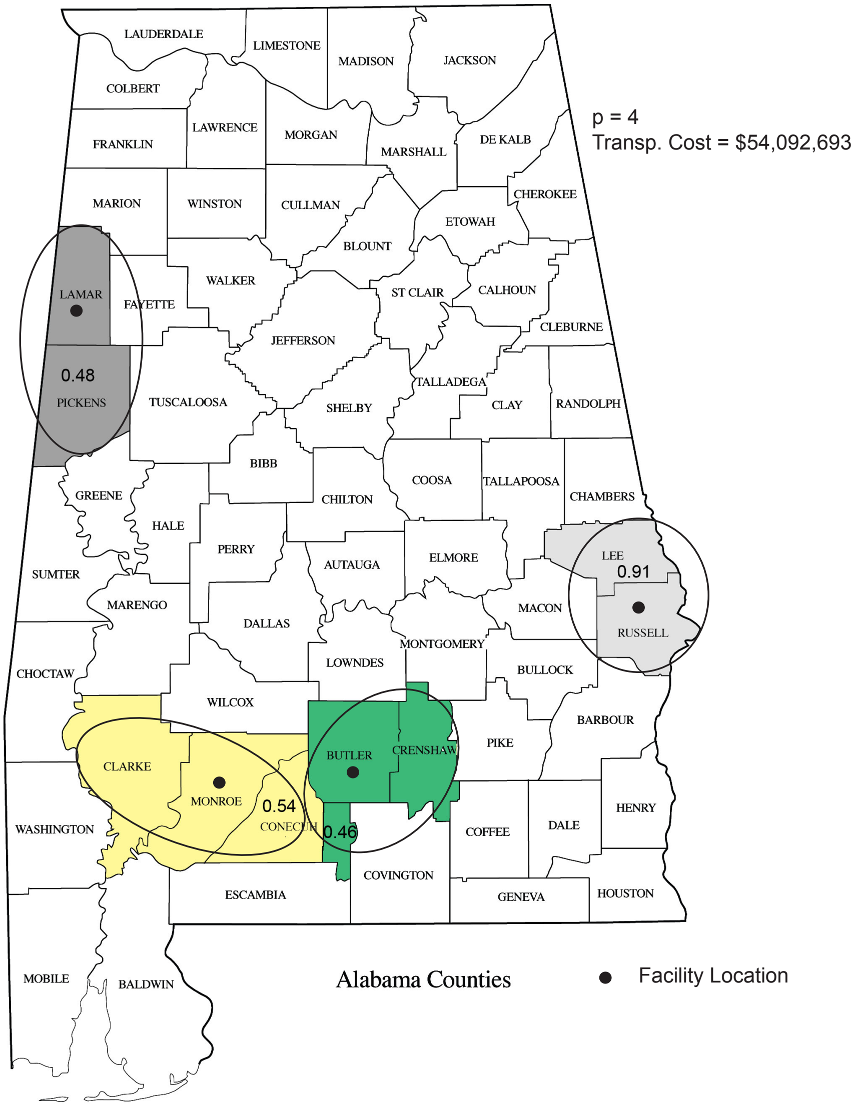


Figure 2.7: Results for p = 4

For p value equal to 5, the model chose Lee, Butler, Monroe, Bibb and Lamar counties as optimal facility locations. The results follow the pattern as the previous experiments.

Figure 2.8 shows the optimal locations and the regions of supply for the refineries. The time taken to obtain an optimal solution by the model is in seconds for the values of p up to 3. It takes a couple of minutes to solve for values of p up to 5. The solution times are relatively quick and increase along with capacity and number of refineries.

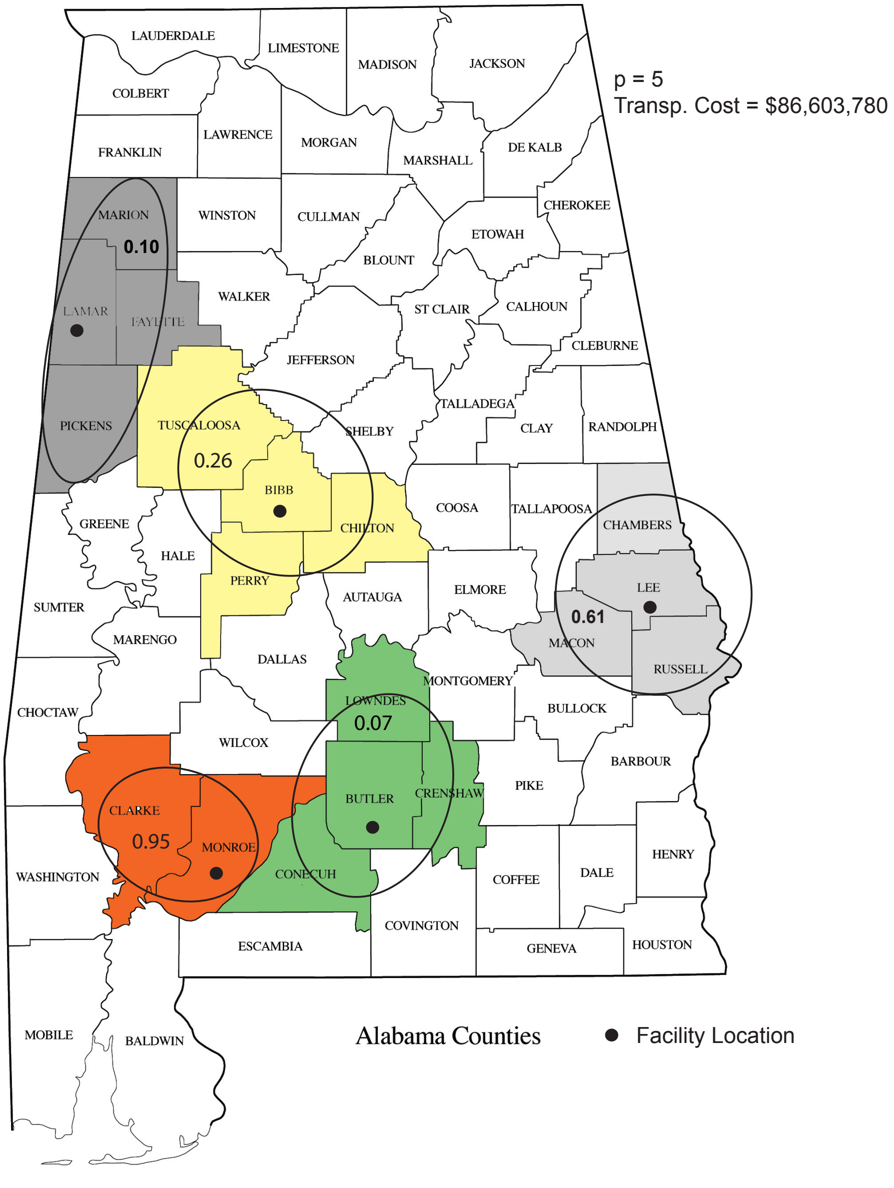


Figure 2.8: Results for p = 5

2.4 Effect of centroids on facility location

In the real world, the pick up points of the feedstock will be randomly located at different parts of the county. But in our model, we have assumed that all the feedstock is obtained from the centroid of the county. So, in order to justify the assumption that centroid to centroid distance does not have a significant impact in selecting the facility location, we performed some experiments using the distances. We created three sets of distances by using both the straight line distances (obtained using the great circle distance formula) and actual distances (obtained using Google Earth). They are as follows:

- Random distances were created by mutiplying distances with the expression 1+Rand(-0.1,0.1)
  i.e $randomd_{ij} = d_{ij} * 1 + Rand(-0.1, 0.1)$
- Second set of distances($1.1d_{ij}$) were obtained by increasing 10% of the distances.
- Third set of distances ($0.9d_{ij}$) were obtained by decreasing 10% of the distances.

We ran the model for these three different scenarios at two different levels of requirement as well as two different levels of raw materials availability (β). The results were the same in terms of facility location and the supply regions for all the three sets of distances. There were variations in the total cost, as we would expect.

CHAPTER 3

REFINERY TECHNOLOGIES

Now, we move to the economic model of the decision support system. Conversion technologies are available to convert any type of biomass into fuels. Significant attention has been given by researchers to develop conversion technologies which are feasible, low cost and less complex to operate. Though most of the refinery technologies are not available on a commercial scale, a few of them have been erected on a smaller scale for research purposes. Using the literature, we have performed an economic analysis for some of the refinery technologies for which data were available. This chapter deals with those refinery technology types which were used in the decision support system. They are as follows:

- Gasification for power production,
- Gasification followed by FT synthesis,
- Simultaneous saccharification and fermentation (SSF),
- Dilute sulphuric acid hydrolysis and fermentation,
- Integrated fast pyrolysis and fermentation, and
- Fast pyrolysis.

There are three capacity levels for each of the refinery technologies. The capacity of the biorefinery (tons of biomass required per day), were obtained from the literature (Craig and Mann, 1996; Ringer et al., 2006; Hamelinck et al., 2004; So and Brown, 1999). Additional capacities were created to make the decision support system more flexible. One is obtained by doubling the base capacity. The other capacity is two-thirds of the base capacity.

3.1 Gasification

Gasification is a manufacturing process that converts carbon-containing materials, such as coal, biomass, or various wastes to a syngas which can then be used to produce electric power, fuels and other valuable products (Gasification technologies council, 2008).The production of syngas is due to the partial combustion of biomass and takes place at temperatures of about $> 700\,^{\circ}\mathrm{C}$ (Craig and Mann, 1996). The reactor in which this process takes place is called a gasifier. The syngas comprises primarily of hydrogen (H_2), carbon monoxide (CO), traces of methane and non useful products like tar and dust. There are several types of gasifiers available for commercial use today. Gasification has a number of significant economic benefits as it converts low-value feedstocks to high value products, thereby increasing the use of available energy in the feedstocks while reducing disposal costs. The ability to produce a number of high-value products at the same time (polygeneration) helps a facility offset its capital and operating costs (Gasification technologies council, 2008). In addition, the principal gasification byproducts (sulfur and slag) are readily marketable providing additional revenues to the plant. The principal issues with biomass gasification is using biomass syngas in a gas turbine. The technologies for biomass syngas cleanup is still evolving and the system used today is highly expensive (Antares Group, 2003).

A Biomass Integrated Gasification Combined Cycle (BIGCC) power plant combines a gasification system with the “combined cycle” electric power system (consisting of one or more gas turbines integrated with a steam turbine). The basic elements of a BIGCC power plant include a biomass dryer (fueled by waste heat), a gasifier for converting the biomass into a combustible fuel gas, a gas cleanup system, a gas turbine-generator fueled by combustion of the biomass-derived gas, a heat recovery steam generator (HRSG) to raise steam from the hot exhaust of the gas turbine, and a steam turbine-generator to produce additional electricity (Larson et al., 2001). The BIGCC configuration achieves the highest thermal-to-electrical efficiency of any commercial power generation technology on the market today (Antares Group, 2003; Rajvanshi, 1986; Larson et al., 2001).

Gas-to-liquid (GTL) technologies convert hydrocarbon feedstock, such as biomass, natural gas or coal, into a FT syncrude, which is processed further into a range of liquid hydrocarbon products (Wilhelm et al., 2001). The GTL process can be broken into three distinct phases: generation of syngas, F-T synthesis, and upgrading (Sousa-Aguiar et al., 2005). Syngas generation is done with the help of gasifaction systems explained earlier. Fischer-Tropsch is a method of converting syngas into hydrocarbon products. The syngas from the gasifier is fed into a F-T reactor and is reacted in the presence of an iron or cobalt catalyst, which converts it into a paraffin wax that is then upgraded (hydrocracked) to make a variety of products. The range of products possible to create from F-T includes light hydrocarbons, methane, ethane, liquefied petroleum gas, gasoline, diesel, and waxes.

In our decision support system we have incorporated both BIGCC configuration and the GTL process. Craig and Mann (1996) have analyzed BIGCC configuration to determine commercial potential of gasification systems. They performed the studies in different types of BIGCC systems as mentioned below:

1. High pressure, air-blown gasification with an aero-derivative gas turbine.
2. High pressure, air-blown gasification with an advanced utility turbine.
3. Low pressure indirectly heated gasification with an advanced utility turbine.
4. Low pressure, Air-blown gasification with an advanced utility turbine.

In our decision support system, we have also incorporated circulated fluidized bed (CFB) gasifiers. Hamelinck et al. (2004) has analyzed the production of FT diesel from biomass. In this process, gasification is followed by FT synthesis. Instead of air (N_2,H_2,Water) additional oxygen is added to the gasifier because gasification with oxygen offers benefits in downstream equipment size, compression energy and higher partial pressures for relevant components in Fischer-Tropsch (FT) diesel (Hamelinck et al., 2004). After pretreated, biomass is passed through a gasifier. Biomass is gasified to produce synthesis gas (biosyngas). The gas is then passed through a compressor for tar removal, and it is cleaned of other

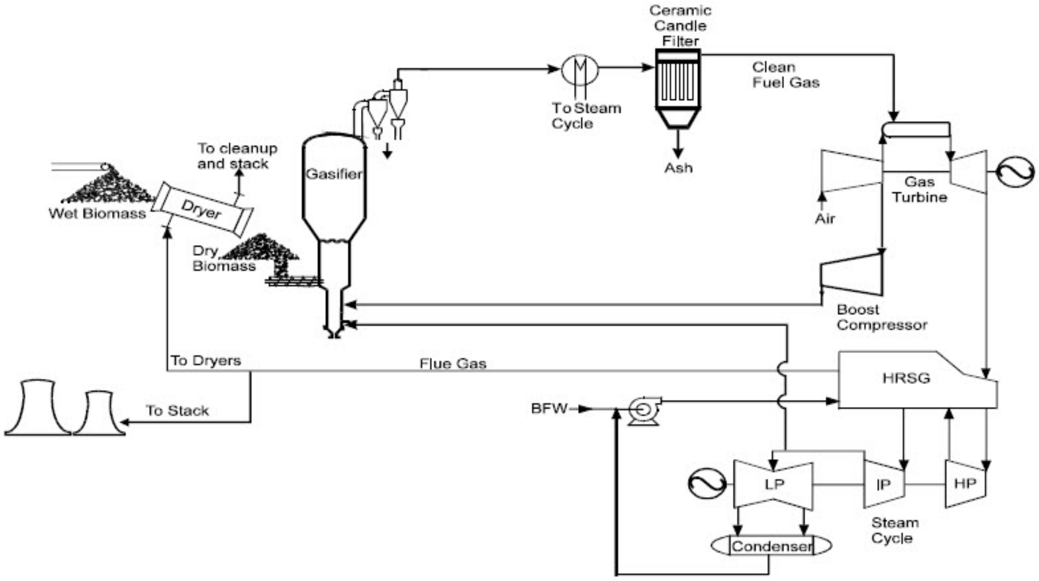


Figure 3.1: High pressure gasifier process flow chart (Craig and Mann, 1996)

impurities. The composition is then modified to fit the specifications for the FT synthesis in the FT reactor. The reactor produces the FT off-gas which is then recycled or combusted to produce electricity. The liquid FT products are treated to produces variety of fuels. The steps involved in the process are shown below.

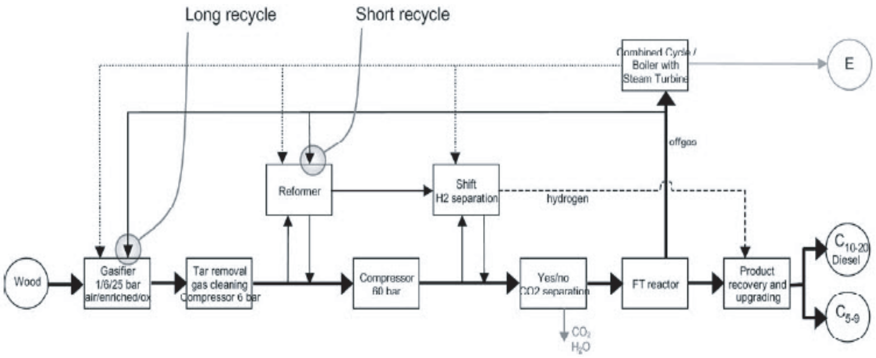


Figure 3.2: FT fuels production process flow chart

3.2 Lignocellulose to ethanol conversion refinery technologies

Extensive research has been done on conversion of lignocellulosic materials to ethanol especially after the 1980 oil crisis (Duff and Murray, 1996; Sun and Cheng, 2002; Eseghlalian et al., 1997; Sivers and Zacchi, 1995). The processing of lignocellulose to ethanol consists of four major unit operations: pretreatment, hydrolysis, fermentation, and product separation/purification (Mosier et al., 2005). Biomass is a mixture of lignin, cellulose and hemicellulose. The purpose of pretreatment is to remove the lignin and hemicellulose, reduce cellulose crystallinity and increase the porosity of materials (McMillan, 1994). This is required to alter the structure of biomass to make cellulose accessible to enzymes. Hydrolysis includes the processing steps that convert carbohydrate polymers into monomeric sugars. During hydrolysis, hemicellulose polymers releases it component sugars, which are fermented to ethanol by microorganisms. Ethanol is then recovered from the fermentation broth by distillation.

There are three basic types of ethanol from cellulose processes – acid hydrolysis and fermentation, enzymatic hydrolysis and fermentation, and thermochemical followed/preceded by fermentation (Badger, 2002). In our decision support system, we have incorporated one variation of each type. They are as follows: dilute sulphuric acid hydrolysis and fermentation, Simultaneous Saccharification and Fermentation (SSF) and Integrated fast pyrolysis and fermentation. Each type is explained in detail in the following sections.

3.2.1 Simultaneous saccharification and fermentation

Cellulose hydrolysis carried out in the presence of fermentative microorganisms is referred to as simultaneous saccharification and fermentation (SSF). So and Brown (1999) have considered an SSF process which has been built into the decision support system. In this process feedstock is fed into an acid prehydrolysis chamber where pretreatment takes place. It is pretreated with dilute sulphuric acid in this chamber to break lignin and cellulose. Then it is passed into the broth for hydrolysis and fermentation. Batch culture of

Trichoderma reesei is utilized for cellulase production (Hinman et al., 1992). During the hydrolysis, three steps take place: adsorption of cellulase enzymes, biodegradation of cellulose to fermentable sugars and desorption of cellulase (Sun and Cheng, 2002). The fermentable sugars (pentose and xylose) generated by the hydrolysis are fermented using genetically engineered *Escherichia coli* (Hinman et al., 1992). After fermentation, ethanol is extracted by distillation. The processes involved are shown below in the flowchart. Compared to acid hydrolysis and fermentation, SSF has the following advantages: increased hydrolysis rate, lower enzyme requirement, higher product yields and shorter process time (Sun and Cheng, 2002). The disadvantages of SSF are incompatible temperature of hydrolysis and fermentation, ethanol tolerance to microbes and inhibition of enzymes by ethanol (Sun and Cheng, 2002).

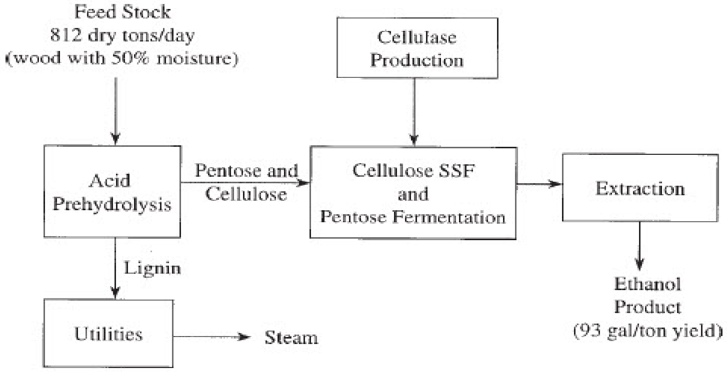


Figure 3.3: SSF process flow chart (So and Brown, 1999)

3.2.2 Dilute sulphuric acid hydrolysis and fermentation

There are two basic types of acid hydrolysis processes: dilute acid and concentrated acid (Badger, 2002). In our decision support system, we have used the process analyzed by Qureshi and Manderson (1995). In this process, heated dilute sulphuric acid at 180 °C is used for the hydrolysis process on the feedstock. Dilute acid processes are conducted under high temperature and pressure, and have reaction times in the range of seconds or minutes, which facilitates continuous processing. During the hydrolysis process, hemicellulose is broken down into its component sugars, pentose and hexose. Then these sugars are passed into the fermentation chamber where it is treated with microorganisms (strain of *Candida shehatae*) to ferment pentose and hexose to ethanol. After fermentation, ethanol is obtained by the process of distillation and membrane separation. By other auxiliary equipment, steam is also produced from the system which, in turn, is used to run a steam turbine to produce electricity. The electricity produced is used to run machines in the plant. Figure 3.4 explains the various steps in this process.

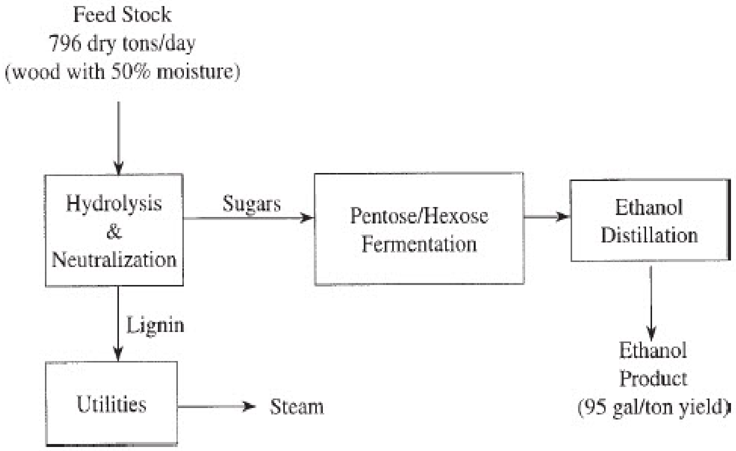


Figure 3.4: Acid hydrolysis process flow chart (So and Brown, 1999)

The advantage of acid hydrolysis and fermentation is that acids can serve both for pretreatment and hydrolysis. But the drawback of these processes are the cost of acids and the requirement to neutralize the acid after treatment to prevent production of inhibitory byproduct, furfural (Dale and Moelhman, 2000).

3.2.3 Integrated fast pyrolysis and fermentation

So and Brown (1999) also analyzed an alternative approach to produce ethanol from lignocellulose by pyrolysis. They studied the Waterloo fast pyrolysis process developed at the University of Waterloo and Resource Transform International Ltd., in Ontario, Canada. The feedstock is fed into acid hydrolysis chamber for pretreatment. The biomass is treated with 5% sulphuric acid at about $80 - 90\,^{\circ}\mathrm{C}$ in the pretreatment process. After this step, a part of the feedstock is passed through for fermentation. The other part of the feedstock is pyrolyzed in a pyrolyzer at 500 °C and then it is passed for extraction of levoglucosan which, in turn, undergoes hydrolysis. After hydrolysis, it passed into the fermentation chamber. In the fermentation chamber, the hexose and pentose sugars from both the parts are fermented and converted into ethanol using two cultures of enzymes (*Saccharomyces cerevisiae* and *Pichia stipitis*). Ethanol is then removed by the process of distillation.

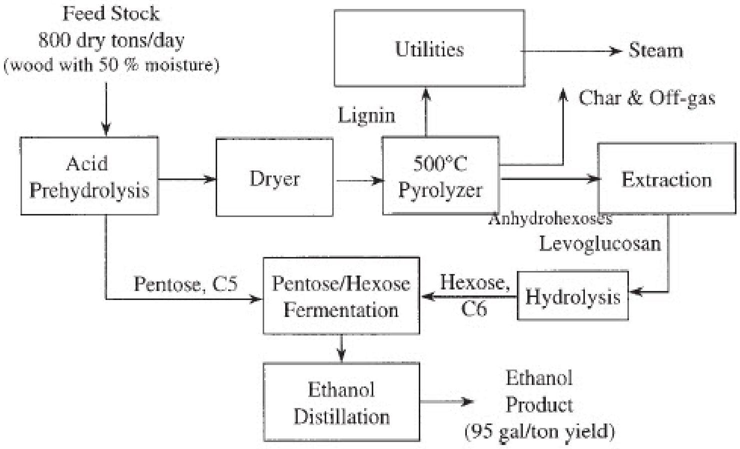


Figure 3.5: Integrated fast pyrolysis process flow chart (So and Brown, 1999)

3.3 Fast pyrolysis

There are lot of studies conducted on fast pyrolysis refinery types. We have used study conducted in NREL for the decision support system. Ringer et al. (2006) have studied the fast pyrolysis process used for the production of bio-oil. The process is composed of five major processing areas: feed handling and drying, pyrolysis, char combustion, product recovery, and steam generation.

In the feed handling section, the biomass is reduced in size to $\leq$ 1-5 mm and dried to 5%-10% moisture. It is then sent to pyrolysis where it is heated to $400 - 500\,^{\circ}$C in an oxygen-deficient atmosphere to degrade the biomass into a mix of gases, bio-oils, and char. Char is removed using high-efficiency cyclones and is combusted to fuel the pyrolysis reaction. To maximize the yield of bio-oils, the reaction is rapidly quenched through heat exchange or direct liquid (e.g., water or recycled bio-oils) injection. The bio-oils are present in the gas stream as aerosols and require scrubbers and/or wet electrostatic precipitator for efficient capture. After cleaning, some of the clean pyrolysis gases are recycled to fluidize the bed; and the remaining gases are combusted for process heat. Where feasible, heat is recovered from the pyrolysis gases to generate steam for electricity production. The figure below shows the processing areas.

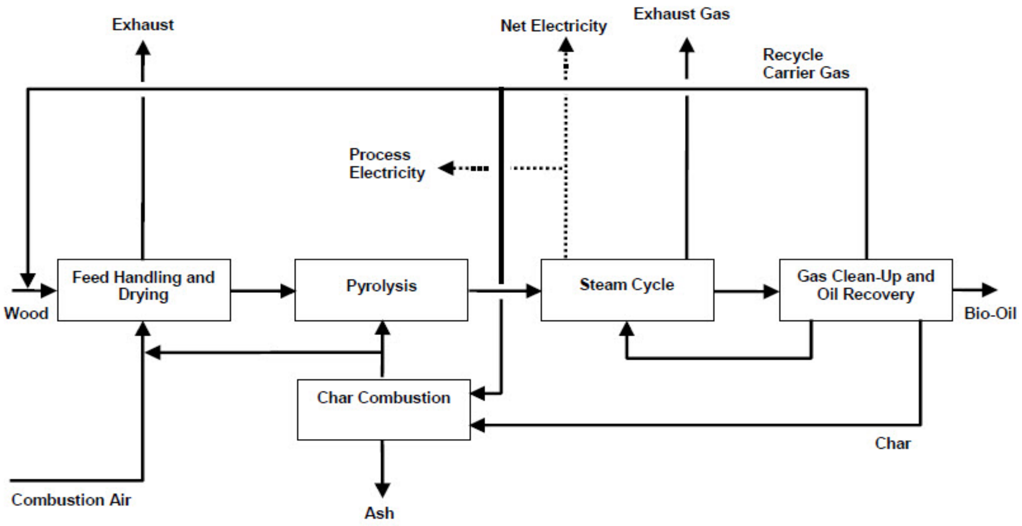


Figure 3.6: Fast pyrolysis block flow diagram (Ringer et al., 2006)

We have incorporated all the above explained refinery technologies into our decision support system. Each refinery type has different products produced from them. Depending on the product the user is interested in, we have provided the user with the list of refinery technologies to choose from. We have performed economic analysis on each type of refinery technology which is explained in detail in the next chapter.

Chapter 4

Economic analysis of refinery technologies

A plant construction will be undertaken only if it promises to be profitable. First, sufficient capital must be promised for the project to bring up all aspects of the plant. It is essential for us to be aware of all the costs associated with operating the plant. In this chapter, investment and plant operation costs involved in all the refinery technologies are explained, as well as cash flow and gross and net profits.

4.1 Assumptions

Data for this decision support system were obtained from published journals (Craig and Mann, 1996; Ringer et al., 2006; Hamelinck et al., 2004; So and Brown, 1999). Because each reference used different sets of assumptions, a common set of assumptions were developed so that the system could be built more robust and future technologies can be added with ease. Some of the general assumptions are tabulated in the following table. More specific assumptions concerning costs and revenues are explained in their appropriate sections.

Economic Assumptions
2008 USD
Technical lifetime = 25 years
Economic lifetime = 20 years
Interest rate = 10%
Modified Accelerated Cost Recovery System (MACRS) depreciation
Federal and State income tax = 40%
Debt to Equity ratio = 0.5
Equity invested in two stages (50% each year)
Plant operation hours = 8000 per year
330 operating days / year
No Production in the first two years of plant construction
50% production in the third year
All the given production output is on the basis of 90% plant capacity except for the fermentation processes.

Table 4.1: Assumptions for Economic Analysis

4.2 Capital Investment

The first major component in an economic analysis is the capital investment. Capital investment is the total amount of money needed to supply the necessary plant and manufacturing facilities plus the amount of money required as working capital for operation of the facilities. Capital costs for all the refinery technologies were estimated using combination of capacity, equipment based cost estimates, contingencies and fees. In the case of gasifiers and fast pyrolysis, the factored estimation method (percentage of delivered equipment cost) is used (Craig and Mann, 1996; Ringer et al., 2006). This method requires determination of the delivered-equipment cost. The other items included in the investment are then estimated as percentages of the total delivered-equipment cost. Capital costs for the lignocellulose to ethanol product refineries were assumed using the order-of-magnitude method. This method related the capital investment of a new plant to the capital investment of a similar previously constructed plant by an exponential power ratio. This power has been found to average between 0.6 and 0.7 for many refineries (Peters et al., 2003). Table 4.2 shows the capital investment required for some of the plant used in the decision support system.

Refinery Type	Capacity (tons/day)	Capital Investment
Integrated fast pyrolysis	800	$91,233,660
SSF	812	$84,622,525
Acid Hydrolysis	796	$88,589,206
High Pressure gasifier	683	$138,914,559
CFB gasifier	1848	$260,670,731
Fast pyrolysis	550	$51,016,723

Table 4.2: Capital Investment values for refinery types (Craig and Mann, 1996; Ringer et al., 2006; Hamelinck et al., 2004; So and Brown, 1999)

4.3 Revenue Estimation

The second component of the analysis is the estimation of revenue. The revenue is generated from the sale of product, or products, by the plant. The total annual revenue from product sales is the sum of the unit price of each product multiplied by its rate of sales. A plant is designed for production of a major product, such as ethanol, or bio-oil, but along with it, additional secondary products are also produced like electricity. Rate of production of these secondary products is determined by the chemistry and operating characteristics of the refinery technology. Though these secondary products may not be huge in volume, they are still used and generate revenues for the refinery. These are also taken into account and added along with the total revenue. The other important thing to note in the economic analysis is that we assume no production for the first two years of operation and 50% production in the third year because, during the start-up period, production rates are very low, the length of the start-up period is usually unknown as well as the year of start-up.

Product prices are best established by market studies and historical data available. In our decision support system, we have obtained the product prices from Energy Information Administration (2009). The historical data is available in the Energy Information Administration (2009) regarding the prices of ethanol, diesel and electricity. Bio-oil and FT diesel are not available as commodities in the fuel market. Hence, the prices of bio-oil and FT diesel are not available and has to be estimated. Bio-oil could be directly used as a replacement fuel for other types of fuels such as #2 and #6 fuel oil or even natural gas. The difference between these fuels is the energy value (heating value) of the fuels. We use this energy difference to estimate the prices. For example, the heating value of #6 heating oil is 153,000 btu/gal and for bio-oil it is 75,000 btu/gal which means #6 heating oil has 2.042 times more energy than bio-oil. Therefore to replace one gallon of #6 heating oil approximately 2.042 gallons of bio-oil is required to obtain the equivalent energy value. Then at equivalent energy value the bio-oil price will follow the same wholesale price of replacement fuel trend. So, we used the #6 heating oil selling price and divided it by 2.042 to obtain the bio-oil selling price. Similarly, we obtained the price of FT diesel as it is used as a replacement fuel for diesel. The heating value of diesel is 130,500 btu/gal whereas that of FT diesel is 124,675 btu/gal. Diesel has 1.047 times more energy than FT diesel. Hence, we obtain the price of FT diesel by dividing the current price of diesel by 1.047. In the decision support system, the user can enter the different values of product unit prices and evaluate the impact of the prices on the revenue and profits by doing sensitivity analysis.

Another major source of revenue to biorefinery is government incentives. Tax incentives and grants are made available to the energy industry as a result of public policy to promote clean technologies. These have been primarily promoted as a method of creating energy independence, reducing the pollutant levels associated with fossil fuels, or both. Significant government incentives are available for the biorefinery operators to encourage entrepreneurs and companies to take up renewable energy projects. Initially such incentives are needed for the new biorefinery markets to emerge. Muehlenfeld (2003) has identified that the investment returns of biorefineries can be hugely affected by these incentives. These incentives are considered to be revenue and are added to the cash flow. Listed below are some of the regulations which are used in the decision support system for some of the refinery technologies.

1. Section 45(a) of Energy Policy Act of 2005

   “ Section 45(a) provides that the renewable electricity production credit for a taxable year is 1.5 cents (adjusted for inflation) for each kilowatt hour of electricity that the taxpayer (1) produces from qualified energy resources at a qualified facility during the 10-year period beginning on the date the facility was originally placed in service."

This regulation is applicable to the gasifier refineries which have their output as electricity.

2. Energy Policy Act of 2005 (H.R. 6)

   "Small ethanol producer (Section 1345-1347): expands the definition of a small ethanol producer to include plants of up to 60 million gallons per year capacity; and creates a production incentive of 10 cents per gallon on the first 15 million gallons of ethanol produced each year."

   This regulation is applicable for the lignocellulose to ethanol conversion refineries.

The newly introduced "Farm Bill 2008" has provided further tax credits to the biorefinery operators which we have not considered in our economic analyzes because the bill was passed in the later part of 2008. This bill provides ethanol producers with a tax credit of $1.01 per gallon of ethanol produced.

4.4 Operating or Production costs

The third component of an economic analysis is operating costs. All expenses directly connected with the manufacturing operation or the physical equipment of a refinery are included in operating costs. These costs are divided into two classifications for easy understanding:

1. Fixed costs
2. Variable production costs

Fixed costs are expenses which are independent of production rate. Expenditures for depreciation, property taxes, insurance, financing (loan interest), and rent are usually classified as fixed costs. These costs, except for depreciation, tend to change due to inflation.

Because depreciation is on a schedule established by tax regulations, it may differ from year to year, but it is not affected by inflation. In our economic analysis, we have used the Modified Accelerated Cost Recovery System (MACRS) to calculate depreciation each year. We also assume debt to asset ratio of 0.5. Each year's loan interest is paid along with some part of the principal. We have assumed the repayment period to be 25 years at 10% interest for the loan. All the other fixed cost values were obtained from the literature of the respective technologies (Craig and Mann, 1996; Ringer et al., 2006; Hamelinck et al., 2004; So and Brown, 1999). The other cost which occurs in the beginning is the startup cost. It is assumed to be 10% of the total investment and is spent in the first year.

Variable production costs include expenses directly associated with the manufacturing operation. This type of cost involves expenditures for raw materials (including transportation, unloading, etc.), direct operating labor, supervisory and clerical labor directly applied to the manufacturing operation, utilities, plant maintenance and repairs, operating supplies, laboratory supplies, royalties, catalysts and solvents. These costs are incurred for the most part only when the plant is operating, hence, the term variable costs.

Careful consideration was taken to develop the variable costs in our decision support system. Expenditure on the raw materials were analyzed in detail. Depending on the biomass requirement of the biorefinery, we can calculate the cost of biomass to be purchased annually. The first three stages of the biomass are harvesting, first stage transport and preprocessing. The United States Forest Service research unit has built a residue trucking model to help truck operators to calculate costs involved while transporting biomass (*Forest Residues Trucking Model*, 2005). The cost for the first three stages of the biomass supply for the model were predicted using the data they have used in their FoRTS model. FoRTS model also provides the list of equipment needed for the various operations like loaders, containers, vans etc. Using this cost data, biorefinery raw material requirement, and equipment information, an optimization model was created to choose the equipment in such a way that least cost per ton is spent on the first three stages. It creates a set of various combinations of equipment needed for the operations and specific requirements of the refinery. We have a facility location model to calculate the variable transportation cost based on the requirement of refinery. The other variable costs like labor, royalties and catalysts were provided by their respective literature of the technologies (Craig and Mann, 1996; Ringer et al., 2006; Hamelinck et al., 2004; So and Brown, 1999). Inflation effects are calculated depending on the current inflation rate entered by the user. The costs are then recalculated for the subsequent years automatically.

4.5 Economic Model

Figure 4.1 shows the economic model of a biorefinery. The total capital investment required for the plant is assumed to occur as a lump sum in the first three years from the start of construction. Cash flows into the refinery as dollars of income (S_i) from the sales of products while the annual costs for operating the refinery, such as raw material cost and labor cost but not including depreciation, are shown as outflow costs (C_o). These cash flows for income and operating expenses represents rate of flow in dollars per year. The difference between the income and the operating costs ($S_i - C_o$) is the gross profit before depreciation charge.

Depreciation (d) is subtracted as a cost before income tax charges are calculated and is reduced. The resulting gross profit ($S_i - C_o - d$) is taxable. The income tax to be paid depends on the tax rate. In our model, we have assumed the tax rate (ϕ) to be 40% including the state taxes. The remainder after the income taxes are paid ($(S_i - C_o - d)(1 - \phi)$) is the net profit and this is returned to the capital reservoir.

When the depreciation charge (d) is added to the net profit, this makes up the total cash flow. The total generated cash flow returned to the reservoir on an annual basis is

$$A_j = (S_{ij} - C_{oj})(1 - \phi) + d_j \phi$$

where A_j is the cash flow from the project in the year j in dollars, S_{ij} is the sales rate in the year j in dollars, C_{oj} is the cost of operation in the year j in dollars, d_j is the depreciation charge for the year j in dollars and ϕ is the income tax rate.

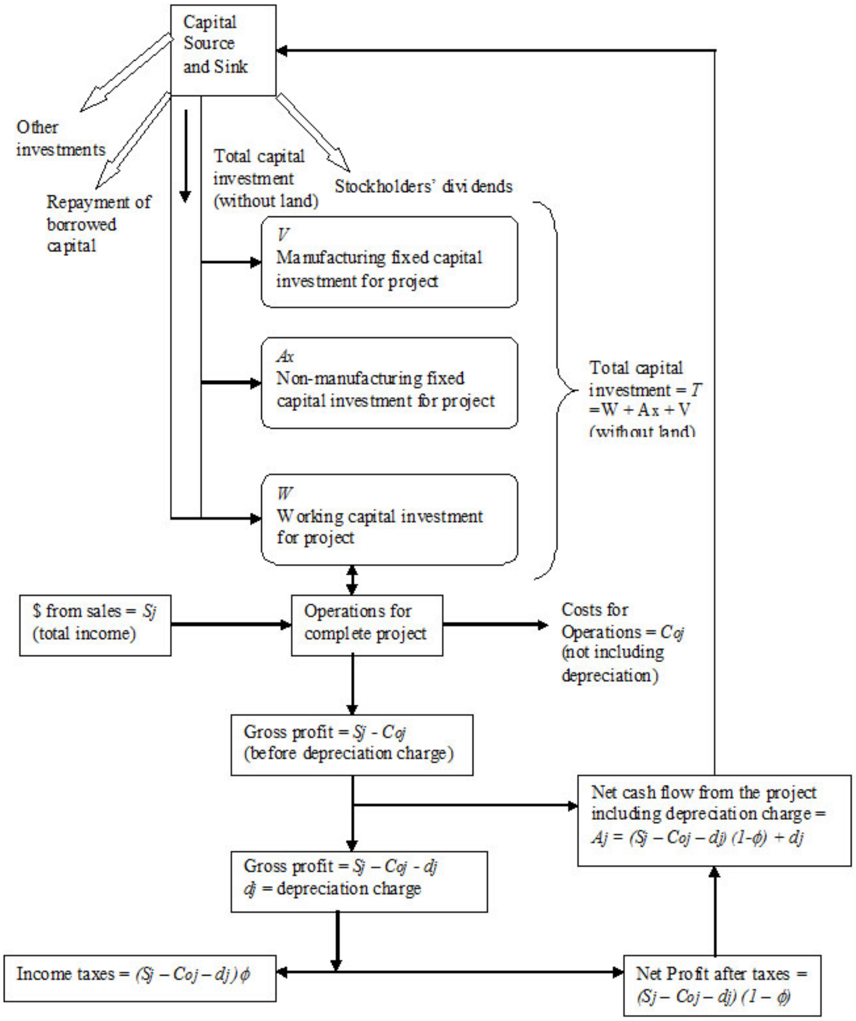


Figure 4.1: Economic Model (Peters et al., 2003)

Using the same methodology, the cash flow for the subsequent years of the refinery is obtained. After calculating the cash flow for the whole life period, net present value of the refinery is calculated in order to take into account the time value of the money. Then the internal rate of return on the investment (IRR) is calculated. It is a rate used to measure the investment worth or profitability. It is defined as the break-even interest rate, i^*, which equates the net present value of a project's cash outflows to the net present value of its cash inflows. It is mathematically expressed as follows,

$$NPV(i^*) = \frac{A_0}{(1+i^*)^0} + \frac{A_1}{(1+i^*)^1} + \frac{A_2}{(1+i^*)^2} + \cdots + \frac{A_N}{(1+i^*)^N} = 0$$

where N is the project life span. In the case of the biorefinery we have assumed N to be 25 years. IRR is very important to investors to know whether they are investing in a profitable venture or not. Using this model, we have calculated the value of IRR for all the refinery types as well as different refinery capacities in each type.

CHAPTER 5

ANALYSIS

5.1 Impact of facility location on IRR

The Decision Support System (DSS) gives the user the optimum facility location, transportation cost and the supply counties; but it fails to capture some important aspects of the decision process such as real estate costs, quality of life considerations, and so on. To investigate the sensitivity of the IRR calculations on the location of the plant, we used the model to locate each of the six refinery types in every county. For this experiment, we chose the average capacity of six refinery technology types. They are integrated fast pyrolysis and fermentation (IFP) with a capacity of 800 tons/day, Simultaneous Saccharification and Fermentation (SSF) with a capacity of 812 tons/day, dilute acid hydrolysis and fermentation (ACH) type of refinery with a capacity of 796 tons/day, oxygen fed Circulated Fluidized Bed gasifier (CFB) with a capacity of 1848 tons/day, fast pyrolysis (FP) with a capacity of 567 tons/day and high pressure gasifier (HPG) with a capacity of 1467 tons/day. The product prices of diesel, ethanol and electricity for the experiments were obtained by taking the average of the prices for the past 5 years. The prices of bio-oil and F-T diesel are calculated using the averages of the corresponding fuels as mentioned in Chapter 4. Thus, the prices obtained are diesel price as \$3 per gallon, ethanol price as \$1.80 per gallon, F-T diesel price as \$2.90 per gallon, bio-oil price as \$0.91 per gallon and electricity price as \$70 per MW. We also assumed the percentage of forest and mill residues (β's) available from each of the counties to be 60% and the inflation rate to be 3.1% for the analysis.

We obtained the IRR values and transportation costs as results from the model for each of the counties. We then plotted the IRR of each county as shown in Figure 5.1. We did the same for the transportation costs and plotted them as shown in the Figure 5.2. We

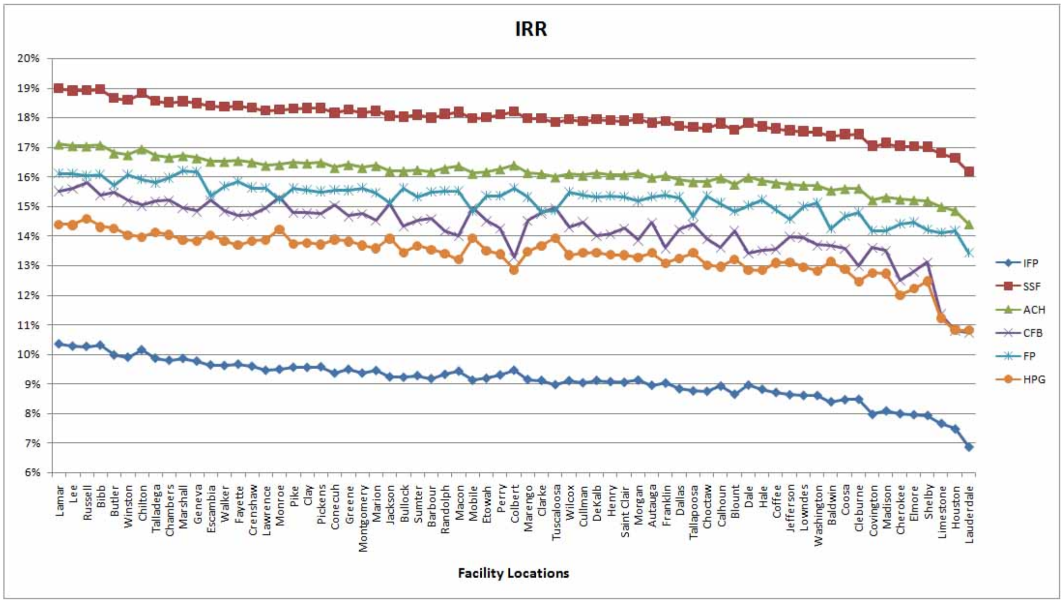


Figure 5.1: Impact of facility location on IRR

can see from the IRR plot that the difference in IRR between the first and last county is approximately 3%. This shows that the location of the biorefinery does not significantly influence the IRR. But considering the large amount of money invested in the biorefinery, even 3% increase in IRR results in large savings.

We can also clearly see from both the plots that certain counties are more favorable for locating a refinery than others. An IRR value of 10% is profitable but may not be sufficient for an investment like this since the technology is considered as a high risk business. For a high risk business, marginal acceptance rate of return for investors is 24%-32% (Peters et al., 2003). From Figure 5.1, we can see that this criteria rules out locating all the six types of refineries at their average capacities. But the SSF refinery has an IRR value above 17% which could attract some investors as it falls within the range (16%-24%) of IRR for medium risk business. Also, increasing the capacity of the SSF refinery from 812 tons/day to 1624 tons/day increases the IRR value above 24% for the same set of inputs. This is important because we can now locate a biorefinery of this type and capacity in Alabama based on logistics— the goal of this research.

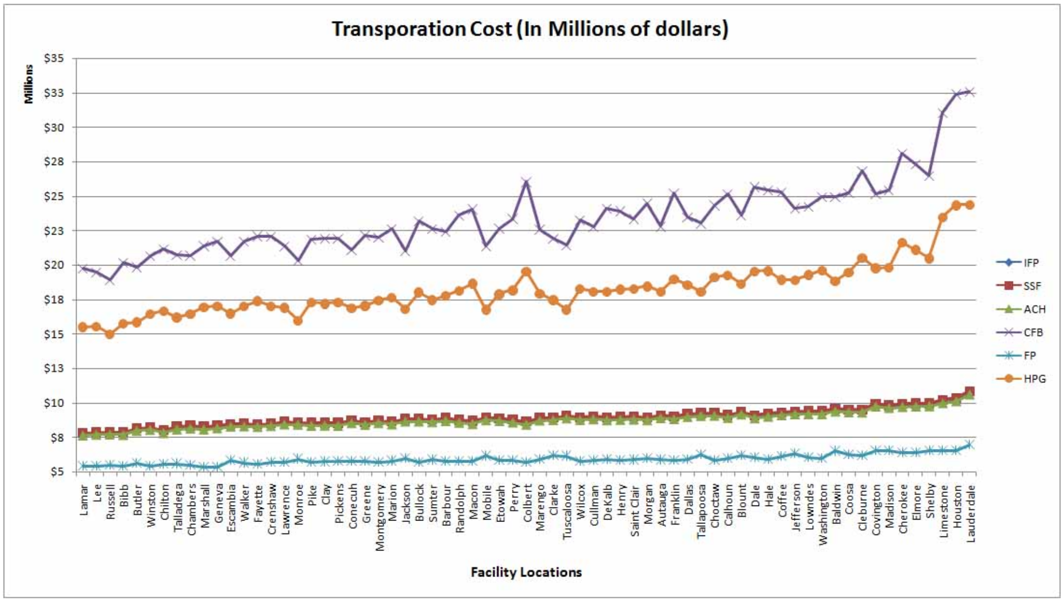


Figure 5.2: Impact of facility location on transportation cost

Using the output from the model, we also ranked the counties based on IRR for each refinery type. We obtained the average rank of each county for all the six refinery types and the results are shown in Table 5.1. We have sorted the results in the table based on the average rank of each county from the experiments. From the table, we can also see that based on the average rank, Lamar county is the best location in the state of Alabama for the six refinery types. The values in the 'number of times in top 10 column' of the table also reiterates the fact that, the counties with richest biomass in the state are the frequently chosen counties for refinery location. As such, the table also provides information regarding alternate locations available for each refinery type.

County Name	IFP	SSF	ACH	CFB	FP	HPG	Average Rank	No of times in top 10
Lamar	1	1	1	3	3	2	1.8	6
Lee	3	4	3	2	4	3	3.2	6
Russell	4	3	4	1	7	1	3.3	6
Bibb	2	2	2	5	6	4	3.5	6
Butler	6	6	6	4	12	5	6.5	5
Winston	7	7	7	8	5	9	7.2	6
Chilton	5	5	5	13	9	11	8.0	4
Talladega	8	8	8	10	11	7	8.7	5
Chambers	10	10	10	9	8	8	9.2	6
Marshall	9	9	9	16	1	17	10.2	4
Geneva	11	11	11	18	2	20	12.2	1
Escambia	13	13	13	7	31	10	14.5	2
Walker	14	14	14	19	13	19	15.5	
Fayette	12	12	12	26	10	25	16.2	1
Crenshaw	15	15	15	25	14	18	17.0	
Lawrence	22	21	22	14	15	16	18.3	
Monroe	20	19	20	6	43	6	19.0	2
Pike	17	18	17	20	19	23	19.0	
Clay	18	17	18	21	20	22	19.3	
Pickens	16	16	16	23	25	24	20.0	
Conecuh	26	25	26	12	21	15	20.8	
Greene	19	20	19	27	22	21	21.3	
Montgomery	25	26	25	24	17	26	23.8	
Marion	23	22	23	30	28	29	25.8	
Jackson	30	30	30	11	45	14	26.7	
Bullock	31	31	31	36	16	33	29.7	
Sumter	29	29	29	31	37	27	30.3	
Barbour	33	33	33	28	26	30	30.5	
Randolph	27	27	27	42	23	38	30.7	
Macon	24	24	24	44	24	46	31.0	
Mobile	36	34	37	15	52	13	31.2	
Etowah	32	32	32	32	32	31	31.8	
Perry	28	28	28	38	33	39	32.3	

Table 5.1: Ranking of counties based on IRR for different refinery technologies

County	IFP	SSF	ACH	CFB	FP	HPG	Avg. Rank	No. of times in top 10
Colbert	21	23	21	60	18	55	33.0	
Marengo	34	35	34	29	39	32	33.8	
Clarke	38	36	39	22	54	28	36.2	
Tuscaloosa	44	44	44	17	56	12	36.2	
Wilcox	39	39	38	37	27	42	37.0	
Cullman	42	42	42	33	30	37	37.7	
DeKalb	37	38	36	45	40	34	38.3	
Henry	40	40	40	43	34	40	39.5	
St. Clair	41	41	41	39	36	41	39.8	
Morgan	35	37	35	49	44	43	40.5	
Autauga	46	46	46	34	38	36	41.0	
Franklin	43	43	43	54	29	50	43.7	
Dallas	48	48	48	40	41	44	44.8	
Tallapoosa	50	50	50	35	51	35	45.2	
Choctaw	51	51	51	48	35	51	47.8	
Calhoun	47	47	47	53	47	52	48.8	
Blount	53	53	53	41	53	45	49.7	
Dale	45	45	45	59	48	56	49.7	
Hale	49	49	49	58	42	57	50.7	
Coffee	52	52	52	56	50	49	51.8	
Jefferson	54	54	54	46	58	48	52.3	
Lowndes	55	55	55	47	49	53	52.3	
Washington	56	56	56	50	46	58	53.7	
Baldwin	59	59	59	51	61	47	56.0	
Coosa	58	58	58	55	57	54	56.7	
Cleburne	57	57	57	62	55	62	58.3	
Covington	62	61	62	52	65	59	60.2	
Madison	60	60	60	57	64	60	60.2	
Cherokee	61	62	61	64	60	64	62.0	
Elmore	63	63	63	63	59	63	62.3	
Shelby	64	64	64	61	62	61	62.7	
Limestone	65	65	65	65	66	65	65.2	
Houston	66	66	66	66	63	66	65.5	
Lauderdale	67	67	67	67	67	67	67.0	

Table 5.2: Ranking of counties based on IRR for different refinery technologies contd.

5.2 Impact of product prices on IRR

How does IRR change with product prices? To find out, we used the model to locate one refinery of each type of product with the average capacity and inflation rate at 3.1%. Certain costs were kept constant in the following analysis on product prices such as woody biomass buying cost to be \$30 and diesel price as \$3 per gallon for the trucks. We also assumed the percentage of forest and mill residues (β's) available from each of the counties to be 60%. All the inputs were entered on a dry-ton basis.

For example, we chose a high pressure gasifier type of refinery with a capacity of 683 tons/day. The product from this type of refinery is electricity. A graph was drawn by plotting price per MW against IRR as shown in Figure 5.3. In 2008, the average wholesale price of electricity per MW was \$83 (Energy Information Administration, 2009). At that price, IRR for the refinery is 15.09% making this type of refinery a potential candidate to be located in the state. But the prices dropped significantly in 2009 and the current price is \$45 per MW. We can see from the graph that operating this type of refinery at this price incurs a loss. Operating the refinery becomes profitable only after the prices crosses \$52 per MW. Also, the profits obtained from this type of refinery are low compared to other refinery types in the state.

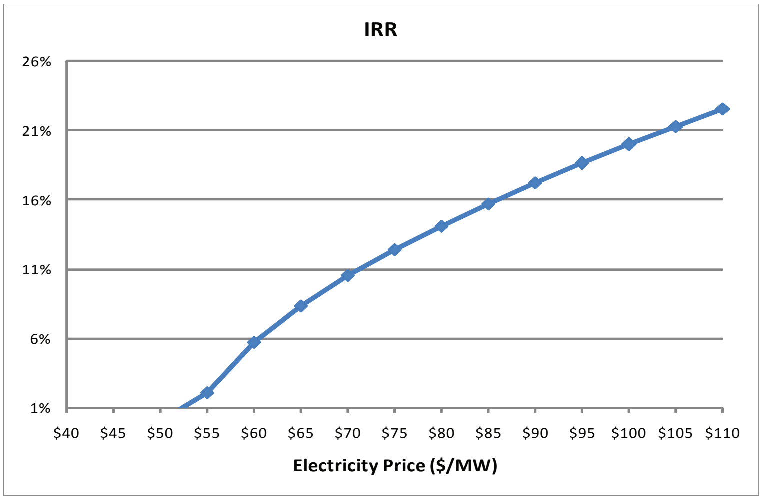


Figure 5.3: Impact of electricity price per MW on IRR

To study the impact of changes in ethanol prices per gallon, we performed experiments to locate an SSF type of biorefinery with a capacity of 812 tons/day. We have used the data obtained from So and Brown (1999) to build the DSS. So and Brown (1999) assumed that 93 gallons of ethanol can be produced from a dry-ton of biomass. This value is slightly higher compared to the refineries in practice. Due to processing and practical constraints, the ethanol obtained from one dry ton of biomass is usually 70-80 gallons. So, we varied the prices for all the three values of ethanol output and obtained the results. The results were plotted in a graph as shown in Figure 5.4. Historically, the prices of ethanol per gallon in the past years have been hovering between $1.80 and $2.50 (Energy Information Administration, 2009). When the price of ethanol touches $2.50, the refineries with ethanol yield of 93 gallons and 80 gallons per dry ton has IRR value more than 24% and for 70 gallons per dry ton the IRR value is 20.58%. Hence at that price, these refineries become attractive to the investors as it falls within the acceptance range for high risk businesses. The current price of ethanol per gallon in 2009 is $1.50, the IRR at this price is negative for 70 gallon per dry ton output and less than 10% for the other values of ethanol output making it less attractive for investors.

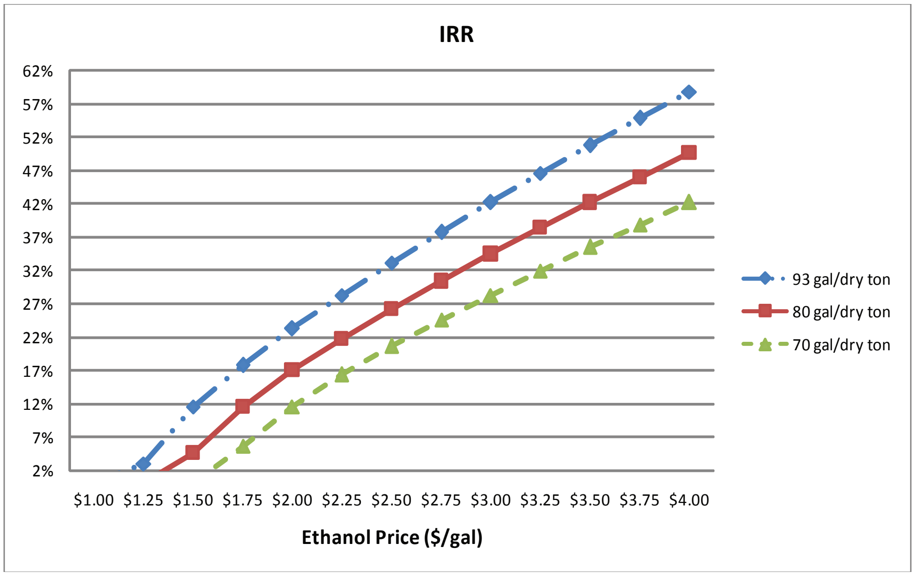


Figure 5.4: Impact of ethanol price per gal on IRR

We can estimate the prices of FT diesel from the prices of diesel by equating their energy values as explained in Chapter 4. The prices of gasoline and diesel are highly variable around the world. For example, in July 2008 the price of diesel touched $4.70 per gallon (Estimated FT diesel price $4.53 per gallon) but the current price is just $2.10 per gallon (Estimated FT diesel price $2.02 per gallon). Hence, there are significant changes in the price and this affects the IRR of the refinery. Therefore, to investigate the sensitivity of IRR on FT diesel prices, we used the model to locate a CFB gasifier type of refinery with a capacity of 1848 tons/day. The results were plotted on a graph. As expected, IRR was found to increase with increase in FT diesel prices. From the graph, we can see that IRR becomes positive between $1.60 and $1.65. Any value below $1.60 results in significant losses for the refinery operator. An increase in the price by $1 causes the IRR to increase by more 10%. Figure 5.5 shows how sensitive IRR is to FT diesel prices.

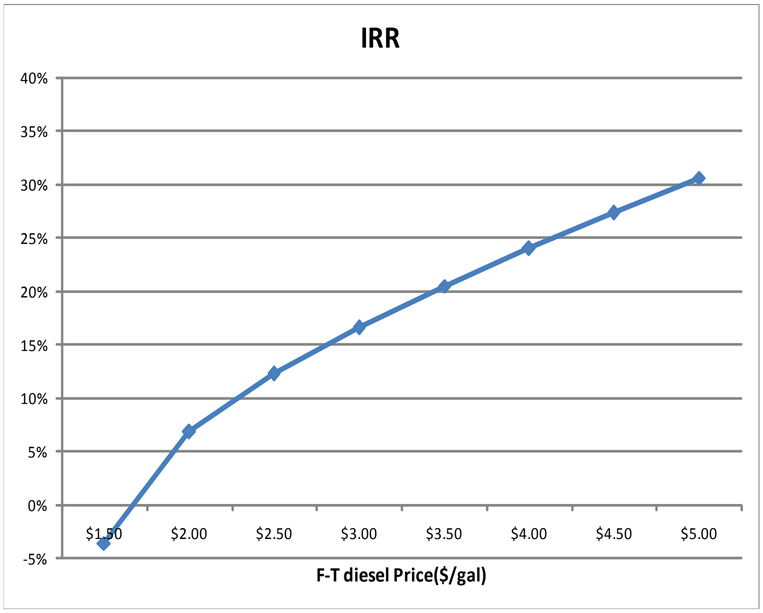


Figure 5.5: Impact of FT diesel price per gal on IRR

Bio-oil can be directly used as a replacement to #2 and #6 oil and can be upgraded to replace diesel and gasoline fuels. In order to study the impact on bio-oil prices, we used the model to locate a fast pyrolysis biorefinery which has a capacity of 550 tons/day. The rest of the inputs were kept constant and the results were obtained. Like the FT diesel prices, the price of bio-oil is estimated from the price of replacement fuels as explained in Chapter 4. The price of the bio-oil follows the same trend as the replacement fuels. Average price of #6 heated oil per gallon in the past ten years is $1.30 (Energy Information Administration, 2009) and the corresponding estimated price of bio-oil is $0.64 per gallon. Operating the refinery at this price incurs loss as shown in the graph. The refinery becomes profitable only after the prices cross $0.80 per gallon (Estimated #6 heated oil price is $1.64 per gallon). From the graph, we can also see that even a 15 cent rise in bio-oil prices increases IRR by approximately 10%. Also, the bio-oil obtained is a low value product and requires further upgrading, if they are to be used as a replacement for diesel and gasoline fuels (Huber et al., 2006). The upgrading process will increase the costs involved and may reduce the values of IRR.

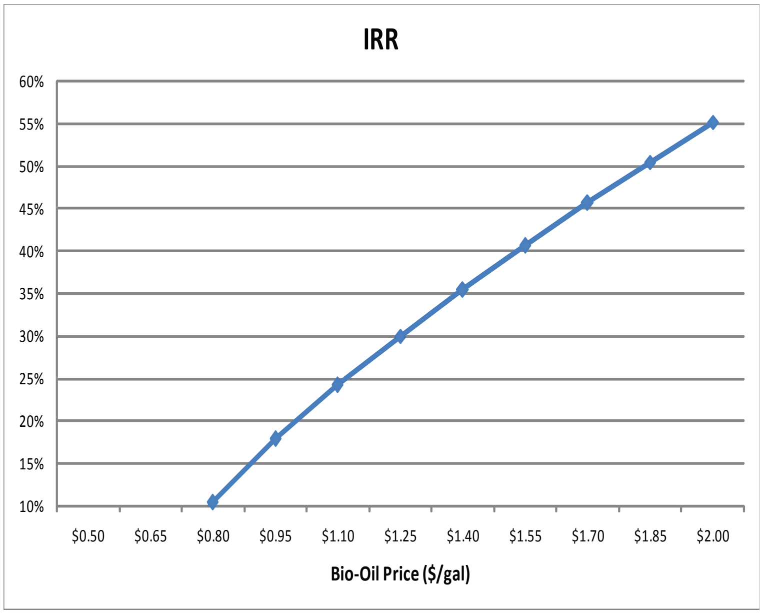


Figure 5.6: Impact of Bio–Oil price per gal on IRR

5.3 Impact of diesel prices

As we have assumed the mode of transportation to be trucks, the diesel price has an impact on the transportation cost which, in turn, affects facility location and IRR. In order to analyze the sensitivity of IRR, we used the same setup that was used in determining the impact of the facility location (Section 6.1) but varied the price of diesel. The diesel price affects the transportation cost of the second stage of transport (\$/ton-mile), from road side to biorefinery, which is used in calculating variable transportation cost. We ran the model for all the six refinery types and obtained the values of variable transportation cost and IRR as results. The transportation cost increases with the increase in biomass requirement of the biorefinery because of the increased amount of truck distances and movements. This is clearly shown in the Figure 5.7 by the difference in transportation costs between the CFB gasifier (1848 tons/day) and the rest of the refinery types which have comparatively less requirement ($<$ 850 tons/day).

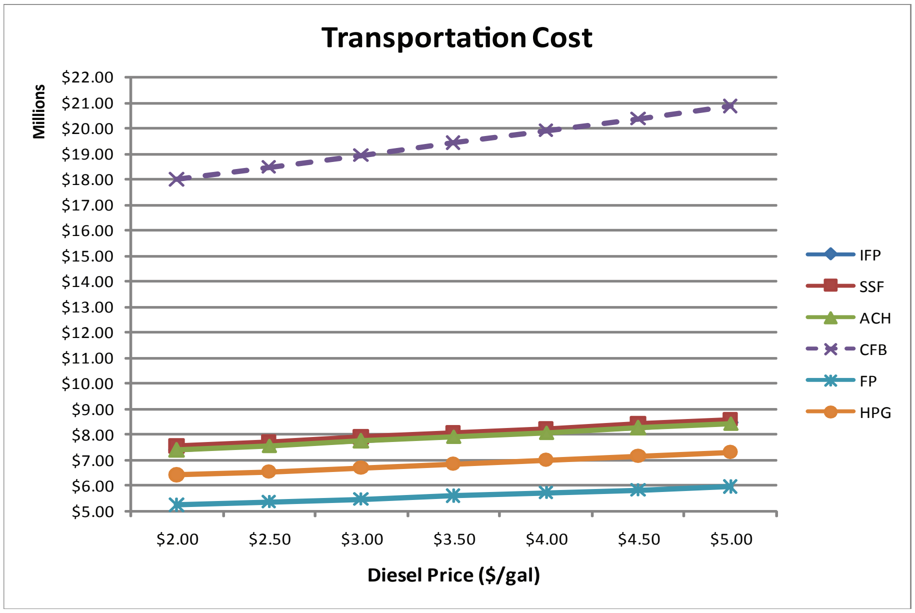


Figure 5.7: Impact of Diesel price per gal on transportation cost

Figure 5.8 helps the user to understand how diesel price per gallon for trucks affects the IRR. The diesel prices have no significant impact on the IRR as shown in the figure. This may be due to the fact that the variable transportation cost involved is small compared to large amount of capital invested in the plant.

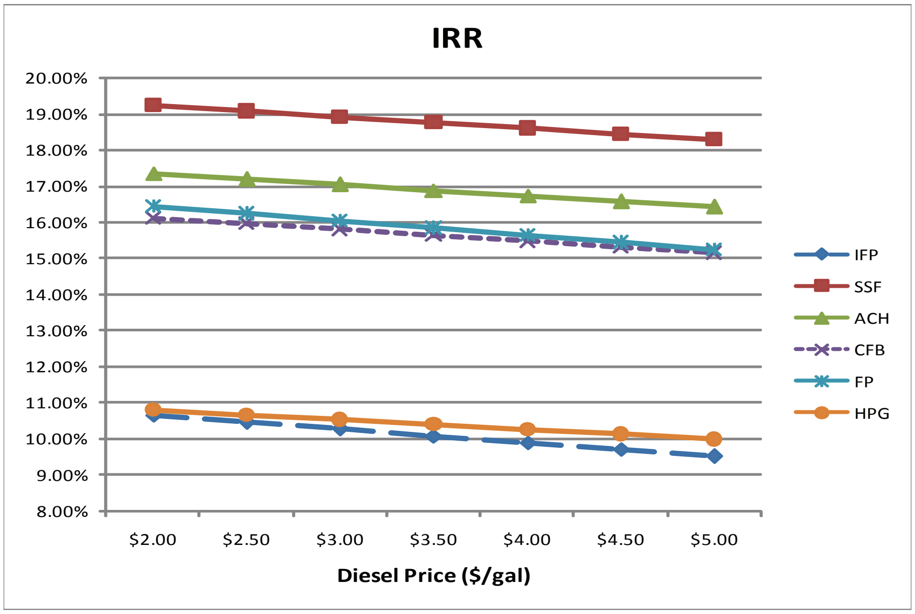


Figure 5.8: Impact of Diesel price per gal on IRR

5.4 Impact of woody biomass buying cost

Increase in biomass buying cost increases the operating cost which, in turn, decreases the profit. To study the impact on biomass buying cost, we used the same setup that was used in determining the impact of the facility location (Section 6.1) but varied the price of woody biomass buying cost. From Figure 5.9, we can see that the biomass buying cost is also one of the factors which affects the IRR. Currently, woody biomass cost is approximately $30 per ton (Muehlenfeld, 2003). A reduction in price by $10 per ton from the current price increases IRR significantly making some of the refineries attractive to investors as it crosses the 16% mark used by some investors. Woody biomass prices have generally not shown the volatility of fossil fuel prices, but they do move up and down based on industrial conditions.

However, the price of woody biomass fuels have been influenced by the prices for fossil fuels (Muehlenfeld, 2003). The value of woody biomass cost could further increase due to the growing markets for alternative uses of woody biomass residues (Muehlenfeld, 2003).

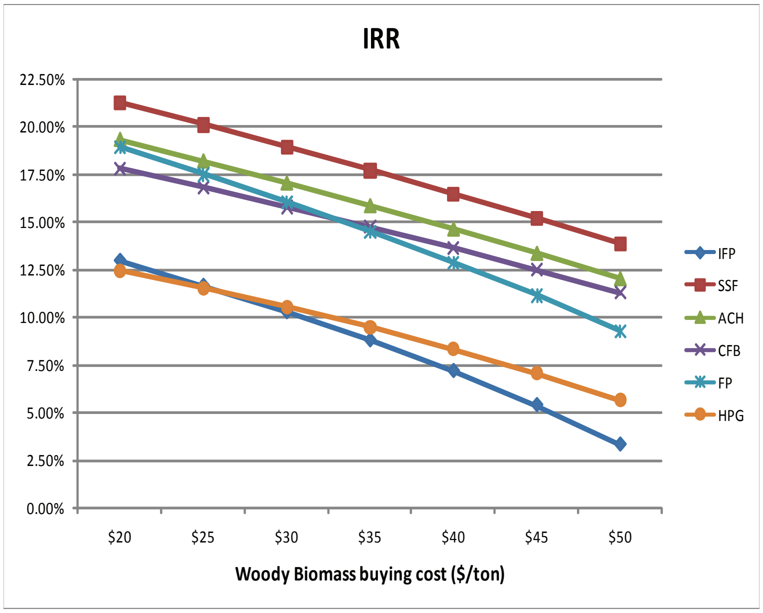


Figure 5.9: Impact of Wood buying cost on IRR

Chapter 6

Decision Support System

In the previous chapters, all the concepts behind the decision support system were explained. In this chapter, the actual user interface for the decision support system is discussed. The system was built using Microsoft Excel 2007 and the Premium Solver addin built by Frontline Systems. In this chapter, each screen in the system is explained in detail.

6.1 Welcome screen

This is the initial screen which will be displayed to the user once the application is opened. In this screen, the title of the decision support system and its use is explained for the user. It also contains the set of instructions that the user has to follow to obtain the needed results. It contains the start button which the user has to click to initiate the process.

Instructions:
1. Click on "START"
2. Enter "Inputs"
3. Click on "SOLVE"

Figure 6.1: Welcome screen snapshot

6.2 Input screen

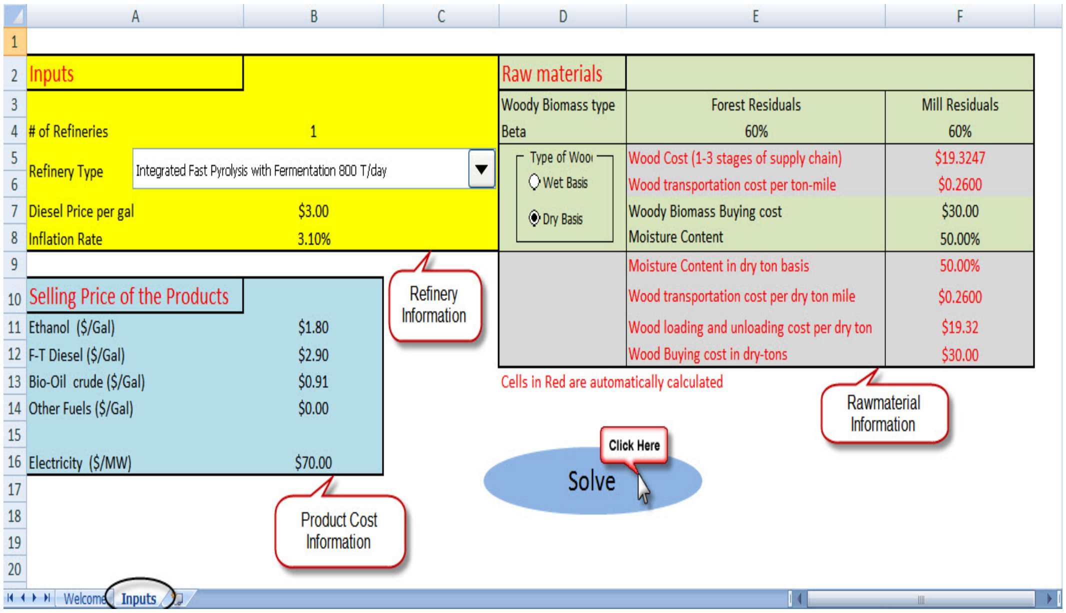
When the user clicks on the start button the input screen is displayed. The input screen is divided into three parts. They are,

- General information
- Raw material information
- Product information

In the general information section, the user enters the number of refineries that he wants to locate in the state of Alabama. Then the user chooses the type of refinery technology which he is planning to use for the refinery from the drop down list. All the refinery technologies along with the capacity is displayed in the list. Each technology has three different capacities of the demand they require per day. Depending on the user, he can choose the size of refinery (small, medium, large) depending on the capacities. The other inputs required in this section are the current price of diesel per gallon and the current inflation rate. The user can perform sensitivity analysis to study the effects of inflation and diesel prices on the profitability by changing these values.

In the raw material information section, the user has to first select the type of data whether it is in wet tons or dry tons. The user has to then enter the percentage of availability of forest and mill residues (β_f, β_m) to be used for biorefinery. The user also enters the cost of obtaining the biomass. The user must also be aware of the moisture content of biomass when it is bought and should be entered into the system. Moisture content affects the cost calculations because it limits the transportation capacity of the trucks. The other costs, wood procurement cost for the first three stages of the biomass supply chain and transportation cost per ton-mile, in this section are automatically calculated based on rest of the data which has been entered into the system. The whole decision support system is built based on dry ton basis, so if the user enters the data in wet tons the system automatically converts them into dry ton basis for further calculations.

In the product information section, the user has to enter the selling price of the products per unit. This section gives the user the flexibility to study the impact of product prices on the profit. Depending on the user's choice of refinery technology in the general information section, the user has to enter the product price per unit in this section. The user doesn't have to enter all the other product information if the technology they have chosen doesn't produce them. After entering all the required information, the user clicks the solve button. The program now enters into solving mode and results will be displayed once the problem is solved.



Inputs

# of Refineries	1
Refinery Type	Integrated Fast Pyrolysis with Fermentation 800 T/day ▼
Diesel Price per gal	$3.00
Inflation Rate	3.10%

Selling Price of the Products

Ethanol ($/Gal)	$1.80
F-T Diesel ($/Gal)	$2.90
Bio-Oil crude ($/Gal)	$0.91
Other Fuels ($/Gal)	$0.00
Electricity ($/MW)	$70.00

Raw materials

Woody Biomass type	Forest Residuals	Mill Residuals
Beta	60%	60%
Type of Woo ○ Wet Basis ● Dry Basis	Wood Cost (1-3 stages of supply chain)	$19.3247
	Wood transportation cost per ton-mile	$0.2600
	Woody Biomass Buying cost	$30.00
	Moisture Content	50.00%
	Moisture Content in dry ton basis	50.00%
	Wood transportation cost per dry ton mile	$0.2600
	Wood loading and unloading cost per dry ton	$19.32
	Wood Buying cost in dry-tons	$30.00

Cells in Red are automatically calculated

Figure 6.2: Input screen snapshot

6.3 Back-end screens

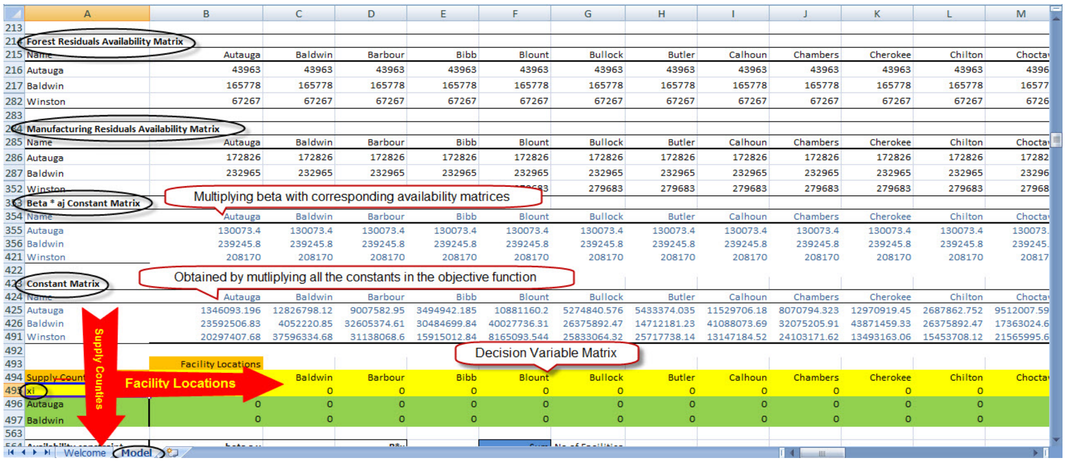
So far, all the screens which the user will be able to see were explained. The rest of the screens are hidden from the user. In the back end i.e. in these screens, the facility location optimization and economic analysis are done. We will see the important screens one by one.

6.3.1 Model screen

In this sheet, the facility location model is built. The data that are already built into the sheet are listed below:

- Distances between counties
- Availability of forest residues
- Availability of mill residues

Based on the input, the rest of the parameters required for the model are obtained. Depending on the refinery type selected in the input sheet, the requirement will be filled in the model sheet automatically. Also, the availability matrices are calculated based on the percentages of forest and mill residues entered in the input. The cost matrix is then generated with these matrices and the costs obtained from the input sheet. The constraints and the objective function are already built into this sheet and will recalculate automatically based on the matrices generated. When the solve button is clicked, all the new data calculations are performed and then the premium solver application is called by the program. The solver then solves the facility location optimization based on the data. The optimized transportation cost, location and the supply counties are thus obtained.



	A	B	C	D	E	F	G	H	I	J	K	L	M
213													
214	Forest Residuals Availability Matrix												
215	Name	Autauga	Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	Chocta
216	Autauga	43963	43963	43963	43963	43963	43963	43963	43963	43963	43963	43963	4396
217	Baldwin	165778	165778	165778	165778	165778	165778	165778	165778	165778	165778	165778	16577
282	Winston	67267	67267	67267	67267	67267	67267	67267	67267	67267	67267	67267	6726
283													
284	Manufacturing Residuals Availability Matrix												
285	Name	Autauga	Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	Chocta
286	Autauga	172826	172826	172826	172826	172826	172826	172826	172826	172826	172826	172826	17282
287	Baldwin	232965	232965	232965	232965	232965	232965	232965	232965	232965	232965	232965	23296
352	Winston					[illegible]	279683	279683	279683	279683	279683	279683	27968
353	Beta * aj Constant Matrix												
354	Name	Autauga	Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	Chocta
355	Autauga	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.
356	Baldwin	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.
421	Winston	208170	208170	208170	208170	208170	208170	208170	208170	208170	208170	208170	20817
422													
423	Constant Matrix												
424	Name	Autauga	Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	Chocta
425	Autauga	1346093.196	12826798.12	9007582.95	3494942.185	10881160.2	5274840.576	5433374.035	11529706.18	8070794.323	12970919.45	2687862.752	9512007.59
426	Baldwin	23592506.83	4052220.85	32605374.61	30484699.84	40027736.31	26375892.47	14712181.23	41088073.69	32075205.91	43871459.33	26375892.47	17363024.6
491	Winston	20297407.68	37596334.68	31138068.6	15915012.84	8165093.544	25833064.32	25717738.14	13147184.52	24103171.62	13493163.06	15453708.12	21565995.6
492													
493		Facility Locations											
494	Supply Count		Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	Chocta
495	xi		0	0	0	0	0	0	0	0	0	0	
496	Autauga	0	0	0	0	0	0	0	0	0	0	0	
497	Baldwin	0	0	0	0	0	0	0	0	0	0	0	
563													

Multiplying beta with corresponding availability matrices

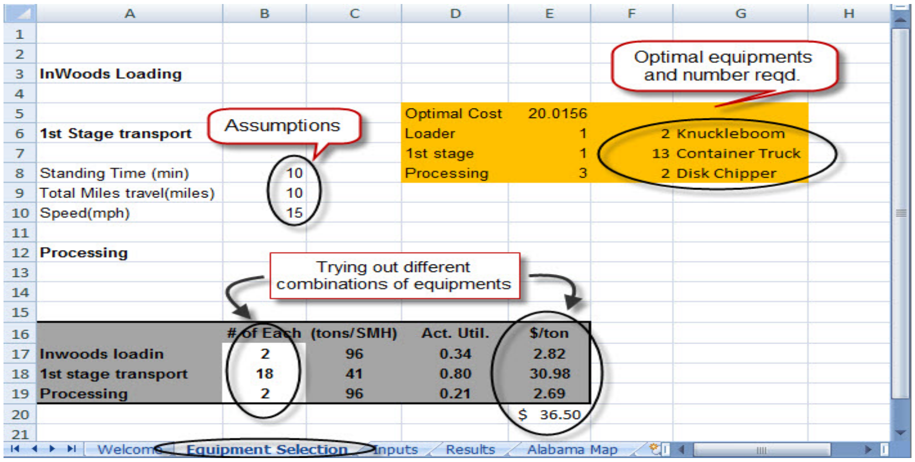
Obtained by mutlipying all the constants in the objective function

Decision Variable Matrix

Figure 6.3: Model screen snapshot

6.3.2 Equipment selection screen

The first three stages of the biomass supply chain resources optimization is done in this sheet. They include the in-woods loading, the first stage transportation and the preprocessing resources optimization. Depending on the refinery type chosen by the user, the annual requirement of biomass is passed onto this sheet. Based on the requirement, the equipment used for the three stages are chosen from the pool of equipment. Data regarding all the equipment for the processes are obtained from the residue trucking model (FoRTS) built by US Forest Service research unit. Capacities, life, investment, costs involved and other miscellaneous costs are all obtained from their model and used in this program. Using this data, cost per ton mile for each equipment can be calculated. With the requirement known, all possible combinations of resources needed to satisfy the requirement is listed out and costs for each combination is calculated. Then the optimal set of equipment is selected from the list so as to minimize the cost associated with operating the machinery. All the above processes are initiated and run in a single module which gives the optimal set of equipment as output.

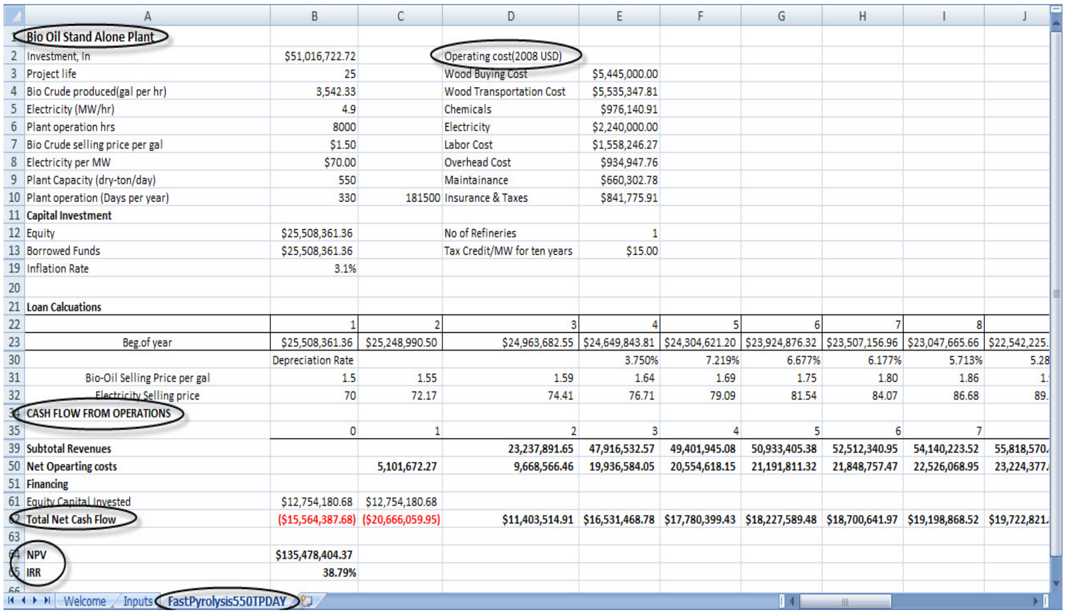


	A	B	C	D	E	F	G	H
1								
2								
3	**InWoods Loading**							
4								
5				Optimal Cost	20.0156			
6	**1st Stage transport**			Loader	1		2 Knuckleboom	
7				1st stage	1		13 Container Truck	
8	Standing Time (min)	10		Processing	3		2 Disk Chipper	
9	Total Miles travel(miles)	10						
10	Speed(mph)	15						
11								
12	**Processing**							
13								
14								
15								
16		**# of Each**	**(tons/SMH)**	**Act. Util.**	**$/ton**			
17	**Inwoods loadin**	**2**	**96**	**0.34**	**2.82**			
18	**1st stage transport**	**18**	**41**	**0.80**	**30.98**			
19	**Processing**	**2**	**96**	**0.21**	**2.69**			
20					$ 36.50			
21								

Figure 6.4: Equipment selection screen snapshot

6.3.3 Analysis Screen

The sheets in which economic analysis is done were grouped together to be called analysis screens. When the user chooses the refinery type and enters the cost data in the input sheet, they are transferred to the respective refinery technology sheet. Then the facility location model calculates the transportation cost which is also transferred to the sheet. The sheet already contains the rest of the costs involved which had been obtained from their respective literature (Craig and Mann, 1996; Ringer et al., 2006; Hamelinck et al., 2004; So and Brown, 1999). Cash flows are generated and rate of return of the investment is calculated.

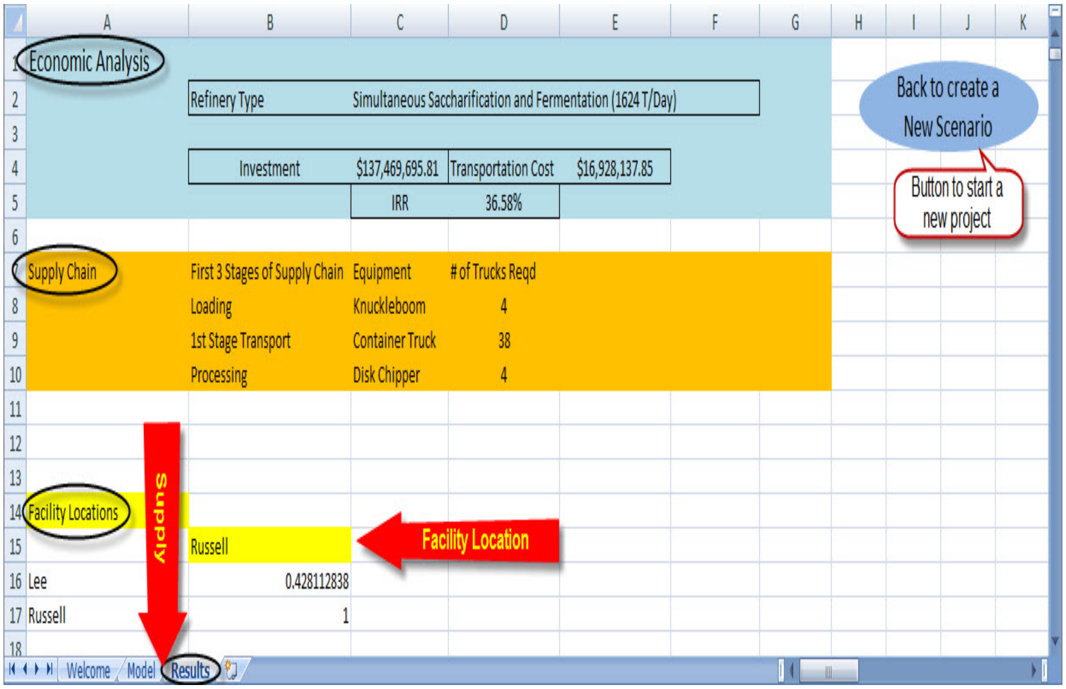


	A	B	C	D	E	F	G	H	I	J
1	**Bio Oil Stand Alone Plant**									
2	Investment, In	$51,016,722.72		Operating cost(2008 USD)						
3	Project life	25		Wood Buying Cost	$5,445,000.00					
4	Bio Crude produced(gal per hr)	3,542.33		Wood Transportation Cost	$5,535,347.81					
5	Electricity (MW/hr)	4.9		Chemicals	$976,140.91					
6	Plant operation hrs	8000		Electricity	$2,240,000.00					
7	Bio Crude selling price per gal	$1.50		Labor Cost	$1,558,246.27					
8	Electricity per MW	$70.00		Overhead Cost	$934,947.76					
9	Plant Capacity (dry-ton/day)	550		Maintainance	$660,302.78					
10	Plant operation (Days per year)	330	181500	Insurance & Taxes	$841,775.91					
11	**Capital Investment**									
12	Equity	$25,508,361.36		No of Refineries	1					
13	Borrowed Funds	$25,508,361.36		Tax Credit/MW for ten years	$15.00					
19	Inflation Rate	3.1%								
20										
21	**Loan Calcuations**									
22		1	2	3	4	5	6	7	8	
23	Beg.of year	$25,508,361.36	$25,248,990.50	$24,963,682.55	$24,649,843.81	$24,304,621.20	$23,924,876.32	$23,507,156.96	$23,047,665.66	$22,542,225.
30		Depreciation Rate			3.750%	7.219%	6.677%	6.177%	5.713%	5.28
31	Bio-Oil Selling Price per gal	1.5	1.55	1.59	1.64	1.69	1.75	1.80	1.86	1.
32	Electricity Selling price	70	72.17	74.41	76.71	79.09	81.54	84.07	86.68	89.
34	**CASH FLOW FROM OPERATIONS**									
35		0	1	2	3	4	5	6	7	
39	**Subtotal Revenues**			**23,237,891.65**	**47,916,532.57**	**49,401,945.08**	**50,933,405.38**	**52,512,340.95**	**54,140,223.52**	**55,818,570.**
50	**Net Opearting costs**		**5,101,672.27**	**9,668,566.46**	**19,936,584.05**	**20,554,618.15**	**21,191,811.32**	**21,848,757.47**	**22,526,068.95**	**23,224,377.**
51	**Financing**									
61	Equity Capital Invested	$12,754,180.68	$12,754,180.68							
62	**Total Net Cash Flow**	**($15,564,387.68)**	**($20,666,059.95)**	**$11,403,514.91**	**$16,531,468.78**	**$17,780,399.43**	**$18,227,589.48**	**$18,700,641.97**	**$19,198,868.52**	**$19,722,821.**
63										
64	**NPV**	**$135,478,404.37**								
65	**IRR**	**38.79%**								

Figure 6.5: Sample economic analysis screen of bio-oil refinery

6.4 Result Screen

The results from the analysis are displayed in three steps in this sheet. First, the results of the economic analysis are displayed which are investment cost, optimized transportation cost and the rate of return of the investment. In the second step, the optimized combination of equipment needed for the first three stages of the supply chain are listed. Along with the list of equipment, the number of equipment required for the hauling operation are also displayed. Finally, the facility location matrix is displayed. In the matrix, the optimized facility locations are displayed on the rows and the supply counties from which raw materials are obtained is displayed in the columns. The matrix is filled with proportion of raw materials obtained from each of the counties for the respective facility locations.


Economic Analysis

Refinery Type Simultaneous Saccharification and Fermentation (1624 T/Day)

Investment	$137,469,695.81	Transportation Cost	$16,928,137.85
	IRR	36.58%	

Supply Chain

First 3 Stages of Supply Chain	Equipment	# of Trucks Reqd
Loading	Knuckleboom	4
1st Stage Transport	Container Truck	38
Processing	Disk Chipper	4

Facility Locations

	Russell
Lee	0.428112838
Russell	1

Figure 6.6: Result screen snapshot

CHAPTER 7

CONCLUSIONS

The goal of this research has been to build a decision support system to answer the question, “Can a biorefinery be located profitably in the state of Alabama?”. The answer to this question is “Yes” for the processes we investigated under certain conditions like product prices, feedstock price and economies of scale. Optimizing the biorefinery location by minimizing transportation cost also helps biorefineries become more competitive. The DSS we have developed also provides information on location in order to minimize the transportation cost of a refinery. It also provides information on the amount of capital investment required for the project, revenues generated from the refinery, costs incurred in operating it and the rate of return on investment in the refinery. Though the decision support system gives the user the optimum facility location, cost and the supply counties; it fails to capture some important aspects of the decision making process such as real estate costs, quality of life considerations, and so on.

Through our research we have identified that the biorefinery locations have less impact (less than 3%) on the values of IRR than one might expect. But considering the large amount of money involved in the business, even small variations in IRR results in significant savings. We have also provided insights on the viable locations and the regions of supply for the refineries. We also found that the optimal locations of the biorefineries are close to the biomass rich areas which would reduce the travel distances and in turn, the transportation cost. With the help of the model, we were able to identify the optimal refinery technology for each of the counties. We were also able to identify the list of counties which were best for each refinery type.

The selling price of the products obtained from the biorefinery is one of the major factors which makes a biorefinery feasible or not. Through our research, we have identified that product prices significantly affect the IRR, which in turn, affects the feasibility. The model helps to determine this feasibility and also captures the sensitivity of profitability to product prices. For example, an increase in FT diesel price per gallon by $1 increases the IRR by 10%. Likewise, any drop in FT diesel price below $1.60 per gallon makes IRR negative, incurring losses. Similarly for bio-oil a small increase in price by 10 cents increases the IRR by 10%. It also helps us identify the threshold values of the product prices which makes the biorefinery profitable. For example, a gasifier type of refinery with a capacity of 683 tons/day which has electricity as output will be profitable only if the price of electricity is greater than $52 per MW. Also, for refineries which have ethanol (yield of 93 gallons per dry-ton) as output the value is $1.25 per gallon. Similarly, a drop in the price of woody biomass buying cost by $10 makes most of the refinery types attractive to potential investors.

The presented decision support system could help in strategic decision-making about locating and operating biorefineries in the state of Alabama or with modifications, in another state. It is particularly advantageous within the early stages of planning a biorefinery plant. The user can:

- analyze the initial situation of the decision problem related to biorefinery operation
- determine the optimal biorefinery location which incurs the least transportation cost
- choose supply counties according to biomass availability and planning options
- estimate the profitability of investments based on realistic assumptions regarding supply chain costs
- adjust biorefinery technology available and types of biomass resources
- estimate which investments in equipment are necessary and profitable
- plan capacities for processing, handling and transport.
- evaluate threshold values for product prices

- react to different developments in the market.

This is the first such decision support system to be built for forest biomass resources to the best of our knowledge. Due to the flexibility of the system, the planner can take current conditions into account each time they use the tool. The process of using this system leads to greater understanding of the processes and relationships. However, the accuracy and significance of the results depend on the available data and on the correctness of underlying estimations and assumptions.

BIBLIOGRAPHY

Allen, J., Browne, M., Hunter, A., Boyd, J., and Palmer, H. (1998). *Logistics management and costs of biomass fuel supply*. *International Journal of Physical distribution & logistics*, 28(6):463–477.

Annual energy outlook, 2006 (2006). Annual energy outlook 2006. Technical report, Energy Information Administration.

Antares Group, I. (2003). Assessment of power production at rural utilities using forest thinnings and commercially available biomass power technologies. Technical report, Prepared for the U.S. Department of Agriculture, U.S. Department of Energy, and National Renewable Energy Laboratory.

Badger, P. (2002). Ethanol from cellulose: a general review. In Janick, J. and Whipkey, A., editors, *Trends in new crops and new uses*. ASHS Press.

Bhat, M., English, B., and Ojo, M. (1992). *Regional costs of transporting biomass feedstocks*. *Liquid Fuels From Renewable Resources; proceeding of an Alternate Energy Conference, 14-15 December 1992, Nashville, Tennessee*, pages 50–57.

Craig, K. R. and Mann, M. K. (1996). *Cost and Performance Analysis of Biomass-Based Integrated Gasification Combined-Cycle (BIGCC) Power Systems*. Technical report, National Renewable Energy Laboratory.

Dale, M. C. and Moelhman, M. (2000). Enzymatic simultaneous saccharification and fermentation (ssf) of biomass to ethanol in a pilot 130 liter multistage continuous reactor separator. *Ninth Biennial BioEnergy Conference, Newyork.*

Daskin, M. S. (2008). *What you should know about location modeling*. *Naval Research Logistics*, 55(4):283–294.

Duff, S. J. B. and Murray, W. D. (1996). Bioconversion of forest products industry waste cellulosics to fuel ethanol: A review. *Bioresource Technology*, 55(1):1 – 33.

Energy Information Administration (2009). Technical report.

Esteghlalian, A., Hashimoto, A. G., Fenske, J. J., and Penner, M. H. (1997). Modeling and optimization of the dilute-sulfuric-acid pretreatment of corn stover, poplar and switchgrass. *Bioresource Technology*, 59(2-3):129 – 136.

Fiedler, P., Lange, M., and Schultze, M. (2007). *Supply Logistics for the industrialized use of Biomass– Principles and Planning Approach*. *IEEE*.

Forest Residues Trucking Model (2005).

Gasification technologies council (2008). Gasfication: Redefining clean energy. Technical report, Gasification technologies council.

Hamelinck, C. N., Faaij, P., Uil, H., and Boerrigter, H. (2004). *Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential*. *Energy*, pages 1743–1771.

Hess, J., Wright, C., and Kenney, K. (2007). *Cellulosic biomass feedstocks and logistics for ethanol production*. *Biofuels, Bioproducts and Biorefining*, 1:181–190.

Hinman, N., Schell, D., Riley, J., Power, A., and Walter, P. (1992). Preliminary estimate of the cost of ethanol production for ssf technology. *Applied Biochemistry and Biotechnology*, 34-35:639–649.

Huber, G. W., Iborra, S., and Corma, A. (2006). Synthesis of transportation fuels from biomass; chemistry, catalysts, and engineering. *Chemical Reviews*, 106(9):4044–4098.

Kumar, A., Cameron, J., and Flynn, P. (2004). *Pipeline Transport of Biomass*. *Applied Biochemistry and Biochemistry*, (27-40).

Larson, E. D., Williams, R. H., and Leal, M. R. L. (2001). A review of biomass integrated-gasifier/gas turbine combined cycle technology and its application in sugarcane industries, with an analysis for cuba. *Energy for Sustainable Development*, 5(1).

Mani, S., Tabil, L. G., and Sokhansanj, S. (2006). Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. *Biomass and Bioenergy*, 30(7):648 – 654.

McMillan, J. (1994). Pretreatment of lignocellulosic biomass. In Himmel, M., Baker, J., and Overend, R., editors, *Enzymatic conversion of biomass for fuels production.* American Chemical Society.

Mosier, N., Wyman, C., Dale, B., Elander, R., Lee, Y., Holtzapple, M., and Ladisch, M. (2005). Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource Technology*, 96(6):673 – 686.

Muehlenfeld, K. J. (2003). *Assessment of Wood-Based Syngas Potential for Use in Combined Cycle Power Plants in Alabama: A Guide For Economic Development Opportunities*. Technical report, Auburn University.

Peters, M. S., Timmerhaus, K. D., and West, R. E. (2003). *Plant design and economics for chemical engineers.* McGraw-Hill Higher Education.

Qureshi, N. and Manderson, G. (1995). Bioconversion of renewable resources into ethanol: An economic evaluation of selected hydrolysis, fermentation, and membrane technologies. *Energy Sources*, 17:241–265.

Rajvanshi, A. K. (1986). *Alternative Energy in Agriculture.* CRC Press.

Ringer, M., Putsche, V., and Scahill, J. (2006). *Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis*. Technical report, National Renewable Energy Laboratory.

Sivers, M. and Zacchi, G. (1995). A techno-economical comparison of three processes for the production of ethanol from pine. *Bioresource Technology*, 51(1):43 – 52.

So, K. and Brown, R. (1999). *Economic Analysis of Selected Lignocellulose-to-Ethanol Conversion Technologies*. *Applied Biochemistry and Biotechnology*, 77-79:633–640.

Sokhansanj, S., Kumar, A., and Turhollow, A. (2006). *Development and implementation of integrated biomass supply analysis and logistics model (IBSAL)*. *Biomass and Bioenergy*, pages 838–847.

Sousa-Aguiar, E. F., Appel, L. G., and Mota, C. (2005). Natural gas chemical transformations: The path to refining in the future. *Catalysis Today*, 101(1):3 – 7. Gas-to-Liquid Technology.

Sun, Y. and Cheng, J. (2002). Hydrolysis of lignocellulosic materials for ethanol production: a review. *Bioresource Technology*, 83(1):1 – 11.

The outlook for energy, 2007 (2007). The outlook for energy. Technical report, ExxonMobil.

Wilhelm, D. J., Simbeck, D. R., Karp, A. D., and Dickenson, R. L. (2001). Syngas production for gas-to-liquids applications: technologies, issues and outlook. *Fuel Processing Technology*, 71(1-3):139 – 148.

Appendices

Appendix A

Manual for using the decision support system

This manual gives users and developers an understanding of how to use the decision support system (DSS) effectively to make decisions and strategies. The manual is structured in such a way that each screen is explained with a screenshot of it from the DSS. The important points to be noted by the user or developer are highlighted in the screenshot. In some shots, explanations are also provided for easy understanding.

Welcome Screen

This is the initial screen which will be displayed to the user once the application is opened. In this screen, the title of the decision support system and its use have been explained for the user. It also contains the set of instructions that the user has to follow to obtain the needed results.

Instructions:
1. Click on "START"
2. Enter "Inputs"
3. Click on "SOLVE"

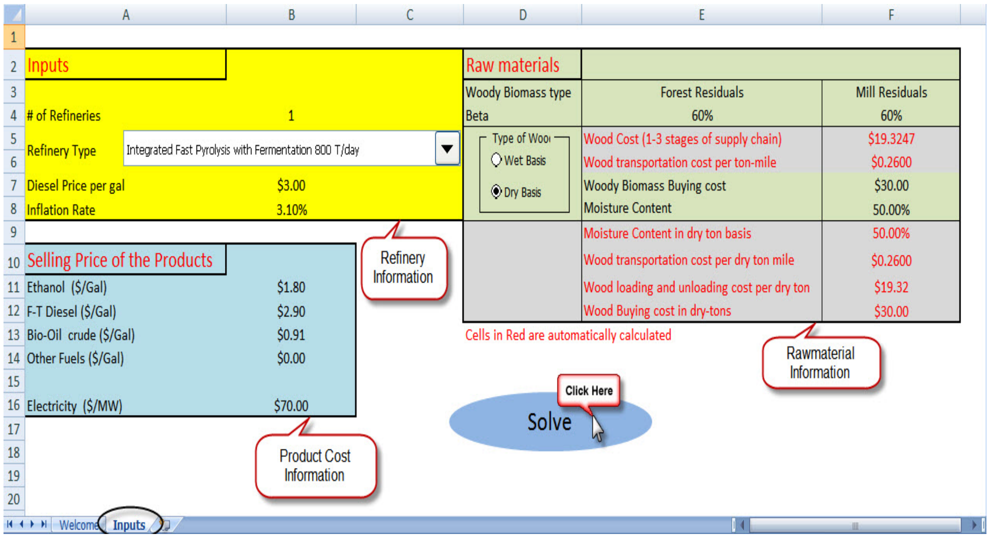
Figure A.1: Welcome Screen Snapshot

Input Screen

When the user clicks on the start button the input screen is displayed. The input screen is divided into three parts. Data collection has to be performed before using the DSS. The necessary data are:

- Refinery information
- Feedstock cost information
- Product cost information

All the data entered in this screen are duplicated in other sheets, as required.



Inputs

# of Refineries: 1
Refinery Type: Integrated Fast Pyrolysis with Fermentation 800 T/day
Diesel Price per gal: $3.00
Inflation Rate: 3.10%

Selling Price of the Products	
Ethanol ($/Gal)	$1.80
F-T Diesel ($/Gal)	$2.90
Bio-Oil crude ($/Gal)	$0.91
Other Fuels ($/Gal)	$0.00
Electricity ($/MW)	$70.00

Raw materials		
Woody Biomass type	Forest Residuals	Mill Residuals
Beta	60%	60%
Type of Woo ○ Wet Basis ● Dry Basis	Wood Cost (1-3 stages of supply chain)	$19.3247
	Wood transportation cost per ton-mile	$0.2600
	Woody Biomass Buying cost	$30.00
	Moisture Content	50.00%
	Moisture Content in dry ton basis	50.00%
	Wood transportation cost per dry ton mile	$0.2600
	Wood loading and unloading cost per dry ton	$19.32
	Wood Buying cost in dry-tons	$30.00

Cells in Red are automatically calculated

Figure A.2: Input Screen Snapshot

Refinery information

Data to be entered in this section are:

- Number of refineries to be located,
- Refinery technology for the biorefinery (selected from a list), and
- Diesel price per gallon used in the trucks.

The choice of refinery technology is linked to a cell in the input sheet. Each refinery type and its capacity are assigned a number. Depending on the refinery technology chosen respective number for that technology is displayed in the cell. This number is used in the Visual Basic code, which triggers the respective values for that technology to be used in the forthcoming calculation.

Feedstock cost information

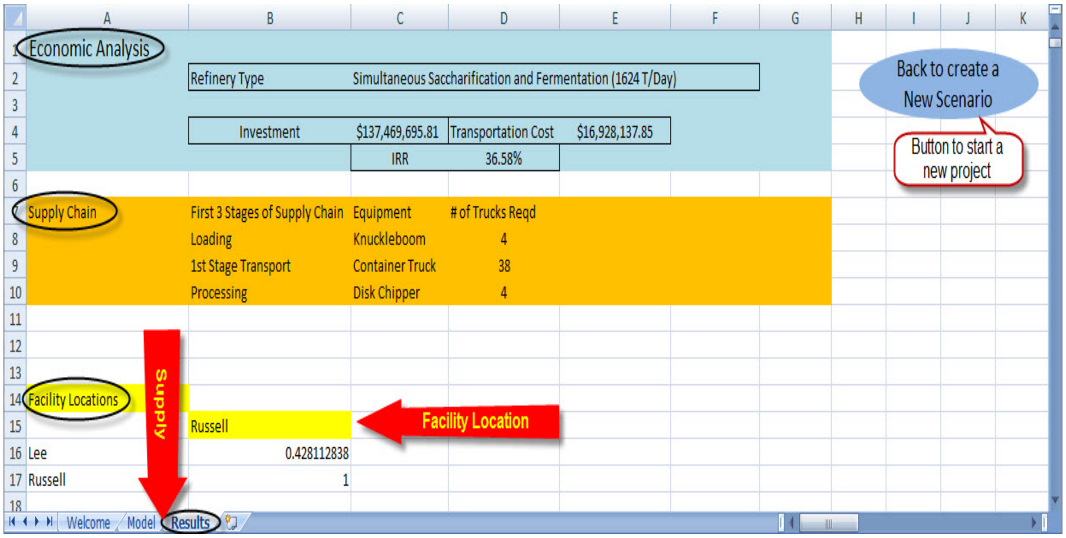
- Select the data in wet-tons or dry-tons
- Percentage availability of forest and mill residues
- Biomass buying cost
- Moisture content

Product cost information

- Depending on the refinery technology, selling price per unit is entered in this section.

Result Screen

The results from the analysis are displayed in three steps in this sheet. First, the results of the economic analysis are displayed which are investment cost, optimized transportation cost and the rate of return of the investment. After this, in the second step the optimized combination of equipment needed for the first three stages of the supply chain are listed. Along with the list of equipment, the number of equipment required for the hauling operation is also displayed. Finally, the facility location matrix is displayed. In the matrix, the optimized facility locations are displayed on the rows, and the supply counties from which raw materials are obtained is displayed in the columns. The matrix is filled with proportion of raw materials obtained from each counties for the respective facility locations. An Alabama map is provided on a separate sheet to help the user to relate the results in a graphical format. A button has been provided in the result screen to help the user start a new project.



Economic Analysis

Refinery Type Simultaneous Saccharification and Fermentation (1624 T/Day)

Investment $137,469,695.81 Transportation Cost $16,928,137.85

IRR 36.58%

Supply Chain

First 3 Stages of Supply Chain	Equipment	# of Trucks Reqd
Loading	Knuckleboom	4
1st Stage Transport	Container Truck	38
Processing	Disk Chipper	4

Facility Locations

	Russell
Lee	0.428112838
Russell	1

Figure A.3: Result Screen Snapshot

Back-end Screens

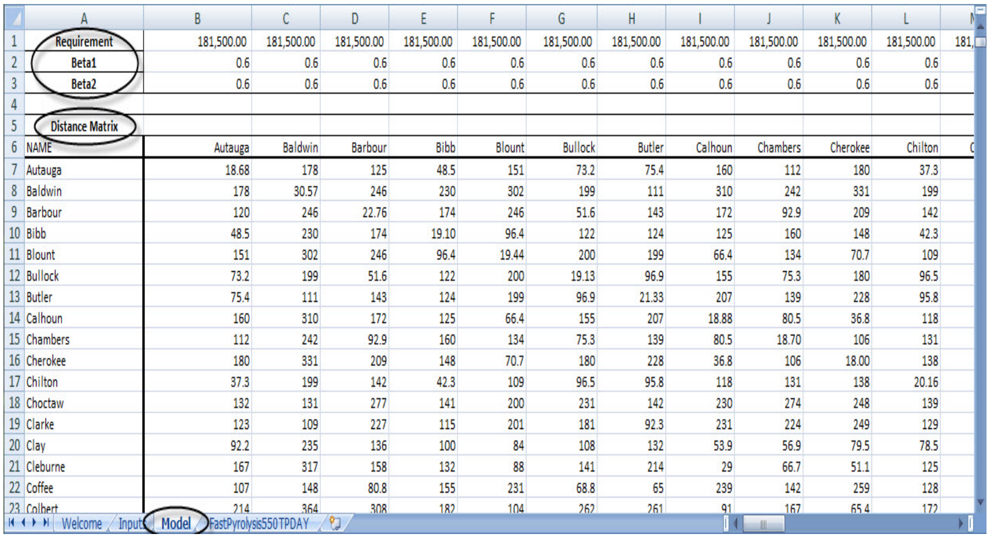
The DSS consists of two models; the facility location model and the economic analysis model. The facility location model is built into a single sheet, i.e. model screen. The economic analysis spans over many sheets. Each sheet representing a refinery capacity and corresponding refinery technology.

Model Screen

In this sheet, the facility location model is built. Various screenshots from different parts of the model screen are shown. The data built into the sheet are listed below.

- Distances between counties
- Availability of forest residues
- Availability of mill residues

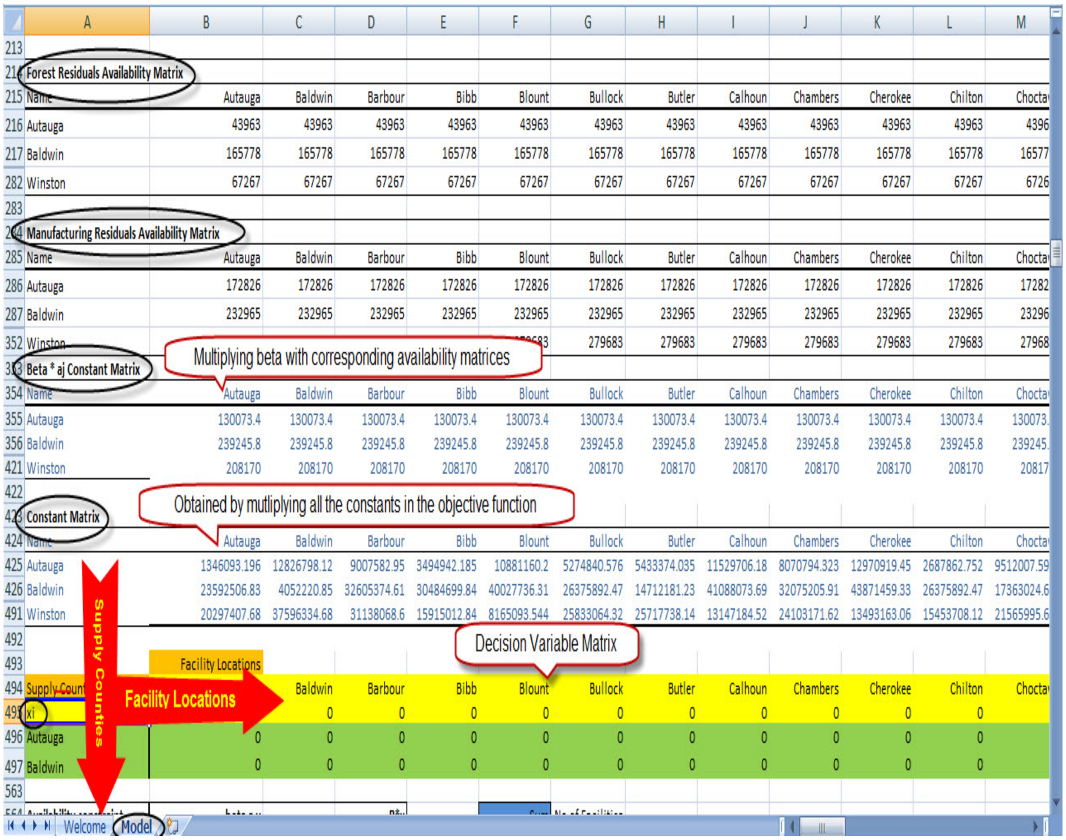
Based on the input, the rest of the parameters required for the model are obtained. Depending on the refinery type selected in the input sheet, the requirement will be filled in the model sheet based on the VB code. Also, the availability matrices are calculated based on the percentages of forest and mill residues entered in the input.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Requirement	181,500.00	181,500.00	181,500.00	181,500.00	181,500.00	181,500.00	181,500.00	181,500.00	181,500.00	181,500.00	181,500.00	181,
2	Beta1	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	
3	Beta2	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	
4													
5	Distance Matrix												
6	NAME	Autauga	Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	C
7	Autauga	18.68	178	125	48.5	151	73.2	75.4	160	112	180	37.3	
8	Baldwin	178	30.57	246	230	302	199	111	310	242	331	199	
9	Barbour	120	246	22.76	174	246	51.6	143	172	92.9	209	142	
10	Bibb	48.5	230	174	19.10	96.4	122	124	125	160	148	42.3	
11	Blount	151	302	246	96.4	19.44	200	199	66.4	134	70.7	109	
12	Bullock	73.2	199	51.6	122	200	19.13	96.9	155	75.3	180	96.5	
13	Butler	75.4	111	143	124	199	96.9	21.33	207	139	228	95.8	
14	Calhoun	160	310	172	125	66.4	155	207	18.88	80.5	36.8	118	
15	Chambers	112	242	92.9	160	134	75.3	139	80.5	18.70	106	131	
16	Cherokee	180	331	209	148	70.7	180	228	36.8	106	18.00	138	
17	Chilton	37.3	199	142	42.3	109	96.5	95.8	118	131	138	20.16	
18	Choctaw	132	131	277	141	200	231	142	230	274	248	139	
19	Clarke	123	109	227	115	201	181	92.3	231	224	249	129	
20	Clay	92.2	235	136	100	84	108	132	53.9	56.9	79.5	78.5	
21	Cleburne	167	317	158	132	88	141	214	29	66.7	51.1	125	
22	Coffee	107	148	80.8	155	231	68.8	65	239	142	259	128	
23	Colbert	214	364	308	182	104	262	261	91	167	65.4	172	

Figure A.4: Model Screen Snapshot

The cost matrix is then generated with these matrices and the costs obtained from the input sheet. The constraints and the objective function are already built into this sheet and will recalculate automatically based on the matrices generated.



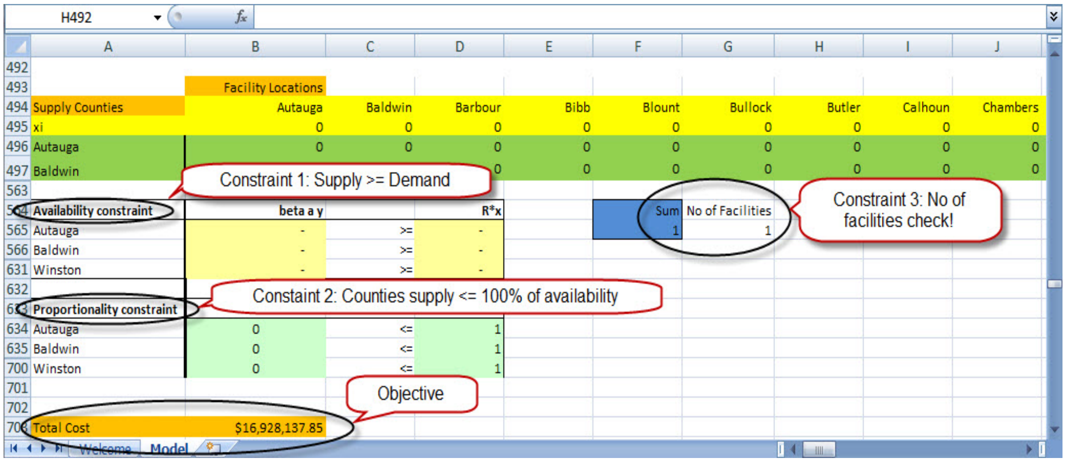
	A	B	C	D	E	F	G	H	I	J	K	L	M
213													
214	**Forest Residuals Availability Matrix**												
215	Name	Autauga	Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	Chocta
216	Autauga	43963	43963	43963	43963	43963	43963	43963	43963	43963	43963	43963	4396
217	Baldwin	165778	165778	165778	165778	165778	165778	165778	165778	165778	165778	165778	16577
282	Winston	67267	67267	67267	67267	67267	67267	67267	67267	67267	67267	67267	6726
283													
284	**Manufacturing Residuals Availability Matrix**												
285	Name	Autauga	Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	Chocta
286	Autauga	172826	172826	172826	172826	172826	172826	172826	172826	172826	172826	172826	17282
287	Baldwin	232965	232965	232965	232965	232965	232965	232965	232965	232965	232965	232965	23296
352	Winston					[illegible]	279683	279683	279683	279683	279683	279683	27968
353	**Beta * aj Constant Matrix**												
354	Name	Autauga	Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	Chocta
355	Autauga	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.4	130073.
356	Baldwin	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.8	239245.
421	Winston	208170	208170	208170	208170	208170	208170	208170	208170	208170	208170	208170	20817
422													
423	**Constant Matrix**												
424	Name	Autauga	Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	Chocta
425	Autauga	1346093.196	12826798.12	9007582.95	3494942.185	10881160.2	5274840.576	5433374.035	11529706.18	8070794.323	12970919.45	2687862.752	9512007.59
426	Baldwin	23592506.83	4052220.85	32605374.61	30484699.84	40027736.31	26375892.47	14712181.23	41088073.69	32075205.91	43871459.33	26375892.47	17363024.6
491	Winston	20297407.68	37596334.68	31138068.6	15915012.84	8165093.544	25833064.32	25717738.14	13147184.52	24103171.62	13493163.06	15453708.12	21565995.6
492													
493		Facility Locations											
494	Supply Count		Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers	Cherokee	Chilton	Chocta
495	xi		0	0	0	0	0	0	0	0	0	0	
496	Autauga	0	0	0	0	0	0	0	0	0	0	0	
497	Baldwin	0	0	0	0	0	0	0	0	0	0	0	
563													

Multiplying beta with corresponding availability matrices

Obtained by mutliplying all the constants in the objective function

Decision Variable Matrix

Figure A.5: Decision Variables matrix Snapshot



H492

	A	B	C	D	E	F	G	H	I	J
492										
493		Facility Locations								
494	Supply Counties	Autauga	Baldwin	Barbour	Bibb	Blount	Bullock	Butler	Calhoun	Chambers
495	xi	0	0	0	0	0	0	0	0	0
496	Autauga	0	0	0	0	0	0	0	0	0
497	Baldwin			0	0	0	0	0	0	0
563										
564	**Availability constraint**	**beta a y**		**R*x**		Sum	No of Facilities			
565	Autauga	-	>=	-		1	1			
566	Baldwin	-	>=	-						
631	Winston	-	>=	-						
632										
633	**Proportionality constraint**									
634	Autauga	0	<=	1						
635	Baldwin	0	<=	1						
700	Winston	0	<=	1						
701										
702										
703	Total Cost	$16,928,137.85								

Constraint 1: Supply >= Demand

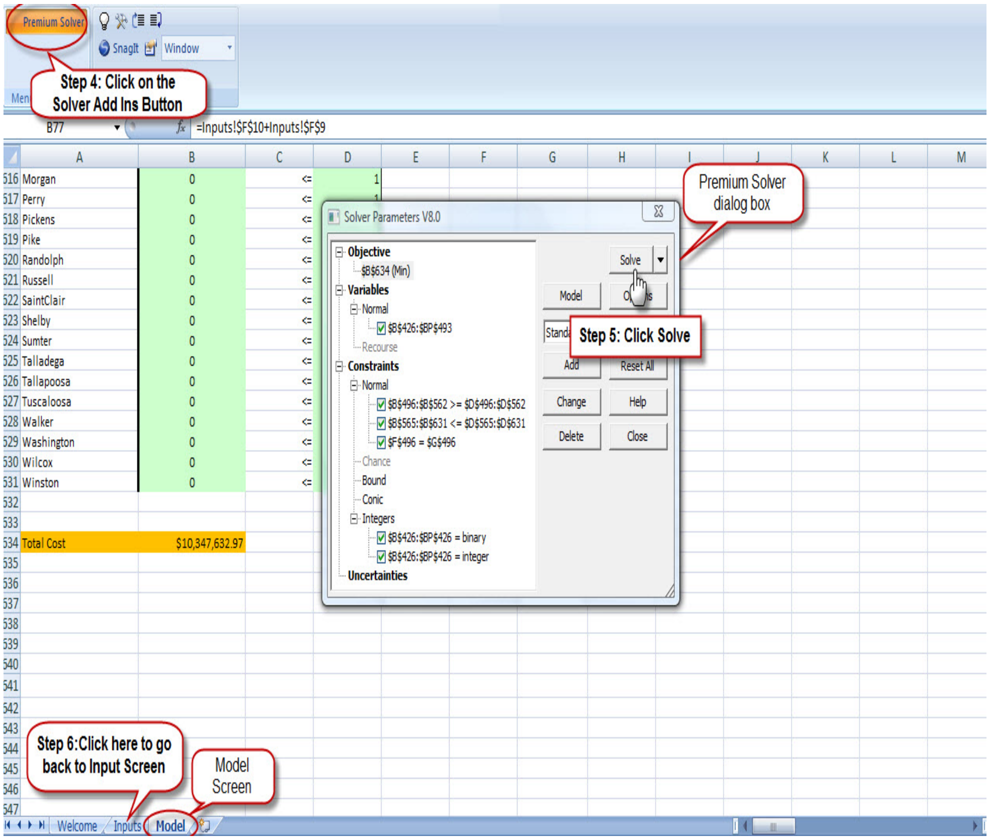
Constraint 3: No of facilities check!

Constaint 2: Counties supply <= 100% of availability

Objective

Figure A.6: Constraints and Objective function Snapshot

When the solve button is clicked, all the new data calculations are performed and then the premium solver application is called by the program. The solver then solves the facility location optimization based on the data. The optimized transportation cost, location and the supply counties are obtained.



Step 4: Click on the Solver Add Ins Button

=Inputs!$F$10+Inputs!$F$9

	A	B	C
516	Morgan	0	<=
517	Perry	0	<=
518	Pickens	0	<=
519	Pike	0	<=
520	Randolph	0	<=
521	Russell	0	<=
522	SaintClair	0	<=
523	Shelby	0	<=
524	Sumter	0	<=
525	Talladega	0	<=
526	Tallapoosa	0	<=
527	Tuscaloosa	0	<=
528	Walker	0	<=
529	Washington	0	<=
530	Wilcox	0	<=
531	Winston	0	<=
534	Total Cost	$10,347,632.97	

Solver Parameters V8.0

- Objective
  - $B$634 (Min)
- Variables
  - Normal
    - ☑ $B$426:$BP$493
  - Recourse
- Constraints
  - Normal
    - ☑ $B$496:$B$562 >= $D$496:$D$562
    - ☑ $B$565:$B$631 <= $D$565:$D$631
    - ☑ $F$496 = $G$496
  - Chance
  - Bound
  - Conic
  - Integers
    - ☑ $B$426:$BP$426 = binary
    - ☑ $B$426:$BP$426 = integer
- Uncertainties

Solve | Model | Options | Add | Reset All | Change | Help | Delete | Close

Step 5: Click Solve

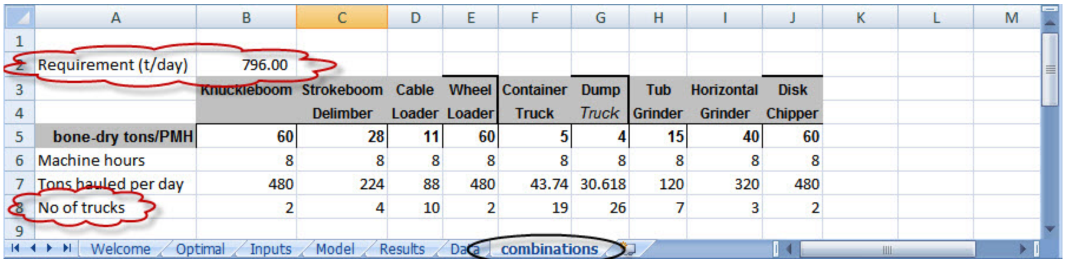
Step 6:Click here to go back to Input Screen

Figure A.7: Model Screen Snapshot with premium solver dialog box

In the screen shot, the premium solver dialog box with all the constraints entered are shown. The DSS is capable of helping the user to decide the optimal refinery technology for a county of the user's choice. In order to incorporate this request from the user, changes have to made in the premium solver dialog box in the constraints. In this case, decision variable is only y and for the value of x, 1 must be entered by the user in the cell corresponding the county of the user's choice rest of the counties x-value will be 0. Then rerun the premium solver. This will give the transportation cost. Trying it out for all the refinery technologies will help the user to obtain the optimal technology for that particular county.

Equipment selection screen

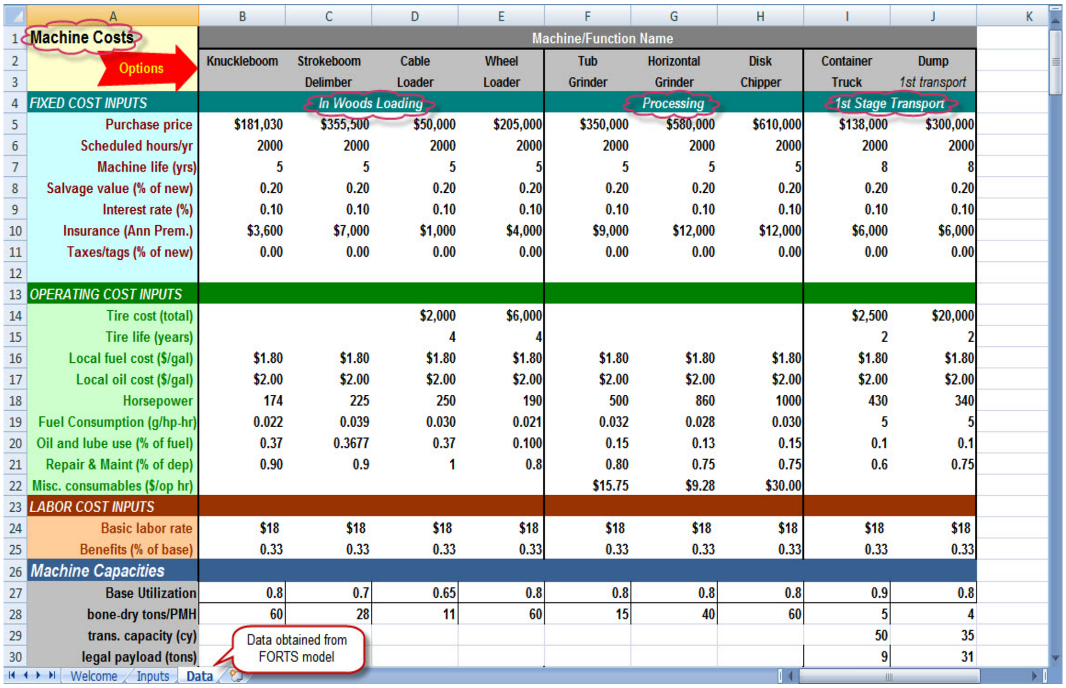
The first three stages of biomass supply chain, in-woods loading, first stage transportation and preprocessing resources optimization are done in this sheet. Depending on the refinery type chosen by the user, the annual requirement of biomass is passed onto this sheet. Based on the requirement, equipment used for the three stages are chosen from a pool of equipment.



	Knuckleboom	Strokeboom Delimber	Cable Loader	Wheel Loader	Container Truck	Dump *Truck*	Tub Grinder	Horizontal Grinder	Disk Chipper
Requirement (t/day)	796.00								
bone-dry tons/PMH	**60**	**28**	**11**	**60**	**5**	**4**	**15**	**40**	**60**
Machine hours	8	8	8	8	8	8	8	8	8
Tons hauled per day	480	224	88	480	43.74	30.618	120	320	480
No of trucks	2	4	10	2	19	26	7	3	2

Figure A.8: Combinations screen snapshot

Data regarding all the equipment for the processes are obtained from the residue trucking model (FoRTS) built by the US Forest Service research unit. Capacities, life, investment, costs involved and other miscellaneous costs are all obtained from their model and used in this program.

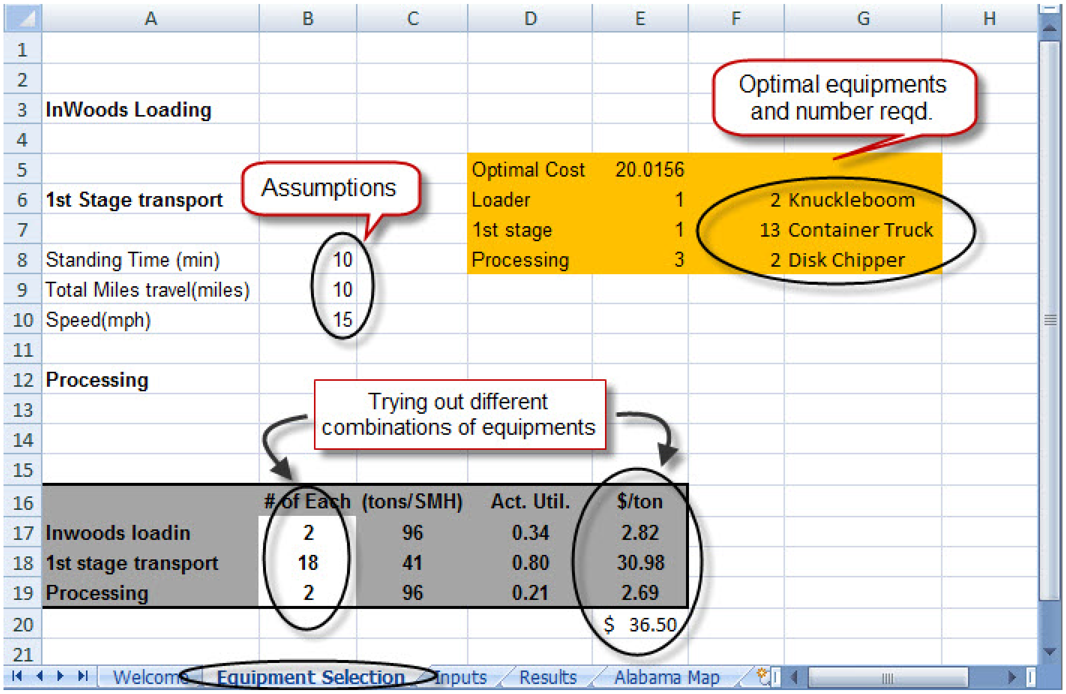


Machine Costs	Machine/Function Name								
Options	Knuckleboom	Strokeboom Delimber	Cable Loader	Wheel Loader	Tub Grinder	Horizontal Grinder	Disk Chipper	Container Truck	Dump *1st transport*
FIXED COST INPUTS		*In Woods Loading*				*Processing*		*1st Stage Transport*	
Purchase price	$181,030	$355,500	$50,000	$205,000	$350,000	$580,000	$610,000	$138,000	$300,000
Scheduled hours/yr	2000	2000	2000	2000	2000	2000	2000	2000	2000
Machine life (yrs)	5	5	5	5	5	5	5	8	8
Salvage value (% of new)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Interest rate (%)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Insurance (Ann Prem.)	$3,600	$7,000	$1,000	$4,000	$9,000	$12,000	$12,000	$6,000	$6,000
Taxes/tags (% of new)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OPERATING COST INPUTS									
Tire cost (total)			$2,000	$6,000				$2,500	$20,000
Tire life (years)			4	4				2	2
Local fuel cost ($/gal)	$1.80	$1.80	$1.80	$1.80	$1.80	$1.80	$1.80	$1.80	$1.80
Local oil cost ($/gal)	$2.00	$2.00	$2.00	$2.00	$2.00	$2.00	$2.00	$2.00	$2.00
Horsepower	174	225	250	190	500	860	1000	430	340
Fuel Consumption (g/hp-hr)	0.022	0.039	0.030	0.021	0.032	0.028	0.030	5	5
Oil and lube use (% of fuel)	0.37	0.3677	0.37	0.100	0.15	0.13	0.15	0.1	0.1
Repair & Maint (% of dep)	0.90	0.9	1	0.8	0.80	0.75	0.75	0.6	0.75
Misc. consumables ($/op hr)					$15.75	$9.28	$30.00		
LABOR COST INPUTS									
Basic labor rate	$18	$18	$18	$18	$18	$18	$18	$18	$18
Benefits (% of base)	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Machine Capacities									
Base Utilization	0.8	0.7	0.65	0.8	0.8	0.8	0.8	0.9	0.8
bone-dry tons/PMH	60	28	11	60	15	40	60	5	4
trans. capacity (cy)								50	35
legal payload (tons)								9	31

Data obtained from FORTS model

Figure A.9: Data from FoRTS v5 snapshot

Using this data, the cost per ton mile for each equipment can be calculated. With the requirement known, the equipment needed for each stage is calculated easily. The next step is to choose the optimal set of equipment to be used for the refinery. This can be achieved by running through all possible combinations of equipment in the three stages and choosing the set which yields the least cost for the first three stages of supply chain.



Optimal equipments and number reqd.

Assumptions

Trying out different combinations of equipments

InWoods Loading

1st Stage transport

Standing Time (min)	10
Total Miles travel(miles)	10
Speed(mph)	15

Processing

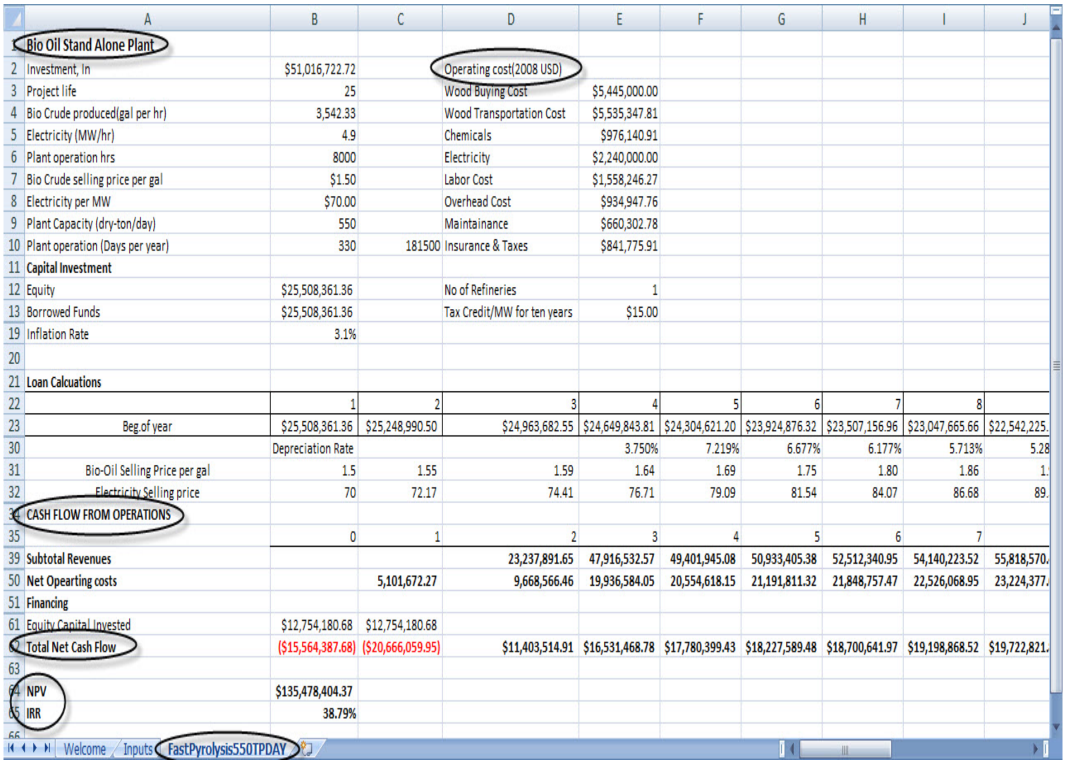
Optimal Cost	20.0156	
Loader	1	2 Knuckleboom
1st stage	1	13 Container Truck
Processing	3	2 Disk Chipper

	# of Each	(tons/SMH)	Act. Util.	$/ton
Inwoods loadin	2	96	0.34	2.82
1st stage transport	18	41	0.80	30.98
Processing	2	96	0.21	2.69
				$ 36.50

Figure A.10: Equipment selection screen snapshot

Analysis Screen

The sheets in which the economic analysis are done were grouped together to be called analysis screens. When the user chooses the refinery type and enters the cost data in the input sheet, they are transferred to the respective refinery technology sheet. Then the facility location model calculates the transportation cost which is also transferred to the sheet. The sheet already contains the rest of the costs involved, which were obtained from their respective literatures. Cash flows are generated and the rate of return of the investment is calculated.



	A	B	C	D	E	F	G	H	I	J
1	**Bio Oil Stand Alone Plant**									
2	Investment, In	$51,016,722.72		Operating cost(2008 USD)						
3	Project life	25		Wood Buying Cost	$5,445,000.00					
4	Bio Crude produced(gal per hr)	3,542.33		Wood Transportation Cost	$5,535,347.81					
5	Electricity (MW/hr)	4.9		Chemicals	$976,140.91					
6	Plant operation hrs	8000		Electricity	$2,240,000.00					
7	Bio Crude selling price per gal	$1.50		Labor Cost	$1,558,246.27					
8	Electricity per MW	$70.00		Overhead Cost	$934,947.76					
9	Plant Capacity (dry-ton/day)	550		Maintainance	$660,302.78					
10	Plant operation (Days per year)	330	181500	Insurance & Taxes	$841,775.91					
11	**Capital Investment**									
12	Equity	$25,508,361.36		No of Refineries	1					
13	Borrowed Funds	$25,508,361.36		Tax Credit/MW for ten years	$15.00					
19	Inflation Rate	3.1%								
20										
21	**Loan Calcuations**									
22		1	2	3	4	5	6	7	8	
23	Beg.of year	$25,508,361.36	$25,248,990.50	$24,963,682.55	$24,649,843.81	$24,304,621.20	$23,924,876.32	$23,507,156.96	$23,047,665.66	$22,542,225.
30		Depreciation Rate			3.750%	7.219%	6.677%	6.177%	5.713%	5.28
31	Bio-Oil Selling Price per gal	1.5	1.55	1.59	1.64	1.69	1.75	1.80	1.86	1.
32	Electricity Selling price	70	72.17	74.41	76.71	79.09	81.54	84.07	86.68	89.
34	CASH FLOW FROM OPERATIONS									
35		0	1	2	3	4	5	6	7	
39	**Subtotal Revenues**			23,237,891.65	47,916,532.57	49,401,945.08	50,933,405.38	52,512,340.95	54,140,223.52	55,818,570.
50	**Net Opearting costs**		5,101,672.27	9,668,566.46	19,936,584.05	20,554,618.15	21,191,811.32	21,848,757.47	22,526,068.95	23,224,377.
51	**Financing**									
61	Equity Capital Invested	$12,754,180.68	$12,754,180.68							
62	**Total Net Cash Flow**	($15,564,387.68)	($20,666,059.95)	$11,403,514.91	$16,531,468.78	$17,780,399.43	$18,227,589.48	$18,700,641.97	$19,198,868.52	$19,722,821.
63										
64	**NPV**	$135,478,404.37								
65	**IRR**	38.79%								

Figure A.11: Sample economic analysis screen of bio-oil refinery Snapshot

Things to know regarding the code

In order to add a refinery technology, the steps to be used are as follows:

1. Collect all the required data for the technology.
2. Using the template and assumptions of the previous technologies, perform economic analysis for the new technology.
3. Attach the sheet to the decision support system.
4. Add it to the list of refinery technologies in the input page.
5. Make changes in the code in 3 areas by adding an extra case statement. Those are for example,
    (a) In the requirement section of the code,
    Case 27
    Sheets(“Model”).Activate
    Range(“B1”).Value = 330 * Worksheets(“unkeconanlysissheetname”).Range(”B9”).Value * nfacilities

(b) In the result display section of the code,

```
Case 26
Worksheets(“Result”).Range(”C2”).Value =“Unknown technology (Capacity”
Worksheets(“Result”).Range(”C4”).Value = Worksheets(“unkeconanalysissheetname”)
.Range(”B2”).Value
Worksheets(“Result”).Range(”D5”).Value = Worksheets(“unkeconanalysissheetname”)
.Range(”B65”).Value
```

(c) Hide the unknown analysis sheet.

To add new equipment in the first three stages of the supply chain, the steps to be used are as follows,

1. Collect the required data for the equipment and add it to the ‘combinations’ sheet as well as the ‘data’ sheet.
2. Add it to a list on the optimal sheet in the appropriate column based on the stages of the supply chain.
3. Calculate the costs involved.
4. Make changes to the code by adding cases similar to the procedure followed for adding a refinery technology.

Most of the code is written to display results except for a few areas where they affect the model. Those areas have been pointed out in the above cases. The code also has comments written side by side to help the developer understand its purpose and also provide an option for the developer to tweak it to obtain new properties, or results.