2012

ECONOMIC MODELING & OPTIMIZATION OF A REGION SPECIFIC MULTI-FEEDSTOCK BIOREFINERY SUPPLY CHAIN

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THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Manufacturing
Systems Engineering in the College of Engineering at the
University of Kentucky

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2012

ABSTRACT OF THESIS

ECONOMIC MODELING & OPTIMIZATION OF A REGION SPECIFIC MULTI-FEEDSTOCK BIOREFINERY SUPPLY CHAIN

The objective of this thesis is to include strategic and tactical level decisions into the biorefinery supply chain design for a specific region while comparing multiple conversion technologies and biomass feedstocks. The allocation of biomass feedstocks, products, and the respective supply chain configuration locations are determined while ensuring the regions monthly biomass availability and product market demand constraints are met. This research considers all actions required to bring the bio-based products to market from harvesting, storing, and processing the biomass to market distribution. Two different conversion technologies are chosen for comparison: one advanced conversion technology and one conventional technology. Potential investors and policy makers will be able to use this region specific tool by maximizing annual profitability to evaluate potential lignocellulosic biomass feedstocks and conversion technologies for the production of energy, fuels, and chemicals. The tool utilizes ILOG OPL software for optimization while interfacing with Microsoft Excel for parameter inputs and results output. From the sensitivity analysis, further insight is gained to what key drivers greatly influence the performance of each supply chain. The results demonstrate the practicality of this tool, which then can be further analyzed through other models such as discrete event simulation.

KEYWORDS: Optimization, Biomass, Supply Chain, Renewable Energy, Jackson Purchase Region

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10/04/2012

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Dedicated to my family

ACKNOWLEDGMENTS

I would like to acknowledge and deeply thank my advisor, Dr. Fazleena Badurdeen, for the sincere encouragement and guidance throughout my Master’s studies. Through multiple feedback iterations on all aspects of my work, she not only motivated me but also challenged me to set the bar higher in my work, all while maintaining the highest level of professionalism. This thesis would not have been possible without her persistent encouragement and guidance. I would like to thank Dr. Ibrahim Jawahir and Dr. Jeffrey Seay for agreeing to be on my committee, as well as for providing valuable feedback and advice during my thesis defense and graduate studies.

I would like to thank all the faculty members and staff of the Institute for Sustainable Manufacturing for their support throughout my time there. I would like to send my deepest gratitude to my research colleagues for their much appreciated support and cooperation.

I am always thankful for my friends and family’s love, affection, and support. I am grateful for my parent’s relentless motivation throughout my life. I would like to thank my loving wife who has believed in me and pushed me to be the person I am today.

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1 INTRODUCTION

1.1 Overview

Over the past decade, energy derived from fossil fuel resources has become an engaging debate due to economic, environmental, and geopolitical reasons. Energy derived from biomass resources, known as bioenergy, is seen as a future energy resource which could help fill this niche. Possible positive impacts of bioenergy include reducing the United States dependence on foreign oil from unstable areas such as the Middle East, in addition to reducing the overall carbon footprint of the country all while involving local rural economies. These biomass resources include all plant and plant-derived materials not just starch, sugar and oil crops already used for food and energy, which includes animal manure (An et al, 2011) as well as a wide variety of industrial-process, municipal-solid, and urban-wood residues (Perlack et al, 2005). Depending on the conversion technology, potential products include electricity liquid transportation fuels, and chemicals with industrial applications.

To progress the production and use of biobased products some governments have proposed and passed legislation requiring a certain percentage of their energy portfolio to come from biomass resources. With the passage of the Energy Independence and Security Act (EISA) of 2007, the US government expanded its Renewable Fuels Standard (RFS) and now will require 36 billion US gallons of biofuels by 2022, of which 21 billion gallons must be derived from non-cornstarch based bioproducts (Biotechnology, 2011). Not only has the federal government in the US has passed renewable energy mandates but 37 of the 50 states plus the District of Columbia and Puerto Rico have enacted a renewable portfolio standard or a renewable portfolio goal (EPA, 2011). The United Kingdom also requires 20% of electricity to come from renewable sources by 2020 as well as cutting 60% of carbon dioxide emissions by 2050 (United Kingdom, 2008). The European Union has adopted a similar energy plan as the Directive 2003/30/CE sets a mandatory quota of biofuels content in traditional liquid transportation fuels to 10% by 2020 as well as a 20% cut of green house gas emissions from all primary energy sources (Londo et al, 2010). Argentinian law 26093 mandates a minimum content of biofuels in gasoline and diesel (Mele et al, 2011). Countries such as China, India, Colombia, Thailand, Mexico, and Venezuela have similar goals for the increase of bioenergy (Olsson, 2007).

As the demand for biobased products such as bioenergy such as energy, fuels, and chemicals is set to increase over the next decade due to said governmental mandates and programs, several issues related to the transportation and processing of such biomass resources will need to be addressed. These issues comprise of low feedstock energy bulk density when compared against conventional fossil fuel sources resulting in higher transportation costs, seasonal variability of biomass supply (Zhu et al, 2011), varying feedstock moisture content (van Dyken et al, 2010), poor storability (Gold and Seuring, 2011) complex product allocation as a result of various conversion technologies (Tay et al, 2011), as well as the risks inherent to relying on a largely agriculturally based system. Due to issues such as these, modeling the bioenergy supply chain, from field to market, has received considerable attention in literature to assess the overall economic, environmental, and societal impacts. Selection of appropriate conversion technology, location, feedstock and product mix, capacity, and respective supply chain configuration has widely been studied both domestically (Parker et al, 2010; Marvin et al, 2010; Zhu et al, 2011) and internationally (Mele et al, 2011; Zamboni et al, 2009a). However, most research only considers strategic level decisions into the supply chain design without considering the variation in monthly biomass availability and fluctuation in market demand. However, modeling can also become too cumbersome when considering all feedstock-to-product pathways (Tripp et al, 2009) some of which are shown in Fig. 1-1 below. Therefore, to properly design the biorefinery supply chain one must include strategic level discussions such as supply chain configuration, types of feedstocks and products, as well as tactical level decisions such as the monthly feedstock and product allocation from field to market, respectively, while investigating one conversion technology at a time.

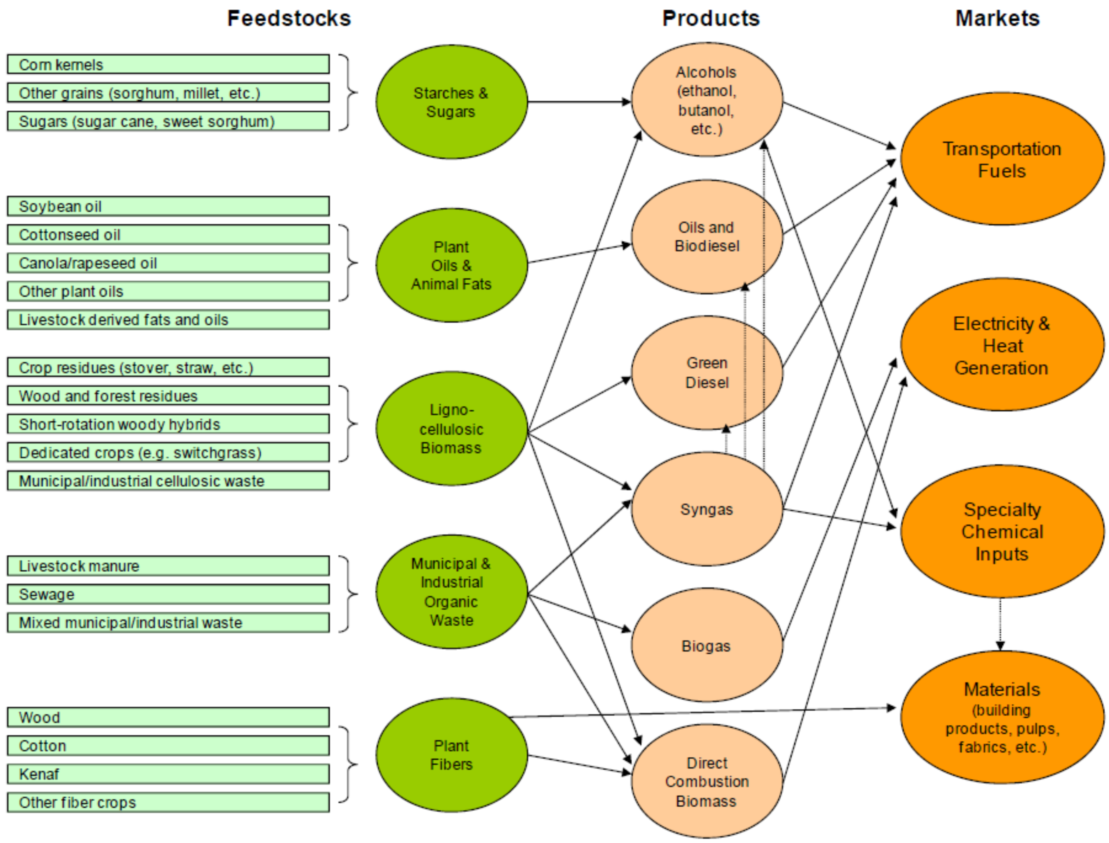


Figure 1-1: Process Flow of Biomass Feedstocks to Biobased Products to Market Applications (Tripp et al, 2009)

1.2 Research Objectives & Questions

The objective of this research is to include strategic and tactical level decisions into the biorefinery supply chain design for a specific region while comparing multiple conversion technologies. The location, allocation of feedstocks and products, size, and respective supply chain configuration are to be determined. By including the regions monthly biomass variability and product market demand into the supply chain design, some issues regarding the production of fuels and chemicals from biomass are addressed without over saturating the market. Therefore through this approach, it is believed a more detailed and overall realistic model can be achieved. Not only will this work address the biorefinery location-allocation supply chain problem but also help answer the following question through a post-optimality analysis.

1. What feedstocks and products should be considered?
2. What region and conversion technology should be studied?
3. How could the performance of the selected supply chain be improved?

4. What influences the supply chain performance the most?
5. How can this work aid policy makers and potential investors in the decision-making process?

The scope of this research will focus on regional level biomass supply for the production of energy, fuels, and chemicals. Doing so should lower the costs related to biomass transportation compared to importing from a surrounding areas. Although past work includes combining biomass resources with fossil fuel resources (Baliban et al, 2010), the focus here is to only investigate biomass resources. Two different conversion technologies will be chosen for comparison; one advanced not commonly used technology and one conventional more readily used technology. Societal and environmental performance and implications are not to be considered in this study.

The remaining sections of the thesis are organized in the following manner. Chapter 2 will provide a literature review on current biomass, bioenergy, and biorefinery supply chain models and techniques. Chapter 3 will discuss the methodology behind this approach in more detail. Chapters 4 and 5 will discuss the case study and modeling scenarios using different conversion technologies, respectively. The results from each scenario with a sensitivity analysis will be presented in Chapters 6 and 7. Observations and conclusions made in this research along with potential paths forward will be discussed in Chapter 8.

2 LITERATURE REVIEW

An extensive literature review has been conducted with regards to various types of supply chain models for the production of energy, fuels, and chemicals from biomass resources. The following sections will discuss the supply chain work completed from field-to-biorefinery (2.1), field-to-market (2.2), conversion technologies (2.3), and collaborative work between supply chain and process models (2.4), followed by a summary (2.5).

2.1 Biomass Supply Chains

The biomass supply chain is made up of several required discrete processes to supply biomass at a biorefinery for production of various biobased products (Rentizelas et al, 2009). Those required discrete processes include:

1) In-field/forest handling and transportation to a more centralized storage location.
2) Storage of the biomass at the more centralized location.
3) Loading of biomass on road transportation vehicles.
4) Transportation of biomass from storage location to biorefinery location.
5) Unloading of biomass at the biorefinery location.
6) Storage at the biorefinery location.
7) Processing of biomass.

Since biomass is required at the biorefinery throughout the course of the year but is harvested only once or a couple to three times a year, it is necessary to store the biomass. Any problems which occur during the storage phase will have exponential negative effects while processing the biomass to respective products due to varying moisture content through microbial fungus and degradation of the biomass. Storage methods include but are not limited to ambient uncovered, ambient covered, warehouse with hot air injection, and silos. The eTransport model (van Dyken et al., 2010), a mixed-integer linear program (MILP) optimization model to minimize overall supply costs, includes the decisions to design the planning of energy systems with multiple energy carriers. Taking into account the varying supply and constant demand of biomass for the use of bioenergy, the eTransport model was able to track the moisture content of the biomass and its relative impact on other biomass properties such as energy content throughout the supply chain. Using chips from spruce as a case study, the supply chain effects from passive drying was shown through the relationship between the moisture and energy content of the biomass. A MILP model to minimize total supply costs of cotton-stalk and almond prunings in Greece was applied to evaluate three most frequently used biomass storage methods: covered-no drying, hot air injection in closed warehouses, and ambient storage (Rentizelas et al, 2009). Even though the ambient storage method bears more health, safety, and technological risks when compared to the other methods studied, it proved to be most economically efficient when utilizing a single feedstock. On the other hand, when a multi-feedstock supply is considered, the closed warehouse with hot air injection storage system proved to be advantageous by mitigating the inherent risks associated with harvesting a single biomass source at specific times of the year, thus providing a constant supply of biomass to the biorefinery.

Due to the vast nature of most nations road transportation infrastructure, transporting biomass via truck seems the most viable option in this manner. However, other forms of transportation may be more appropriate based on average transport distance, biomass density, carrying capacity, and traveling speed of respective vehicles (Allen et al, 2008; Huisman et al, 1997; Tatsiopoulous et al, 2003). Processing of biomass to increase the amount to be transported, improve the handling efficiency, or improve the processing capabilities at the biorefinery include baling, chopping, grinding, and pelletizing. This step can occur at any stage of the biomass supply chain but often precedes the transportation to the biorefinery to decrease the costs of transportation (Rentizelas et al, 2009). Even though pre-processing has positive impacts with regards to transportation and handling, this will not be the focus of this work.

The costs, energy inputs, and greenhouse gas emissions associated with the "field-to-facility" corn stover logistics system were evaluated in Morey et al, (2010) based on a 30 mile radius. When compared against natural gas and coal, using corn stover for the production of heat and power proved to reduce total life-cycle GHG emissions by factors of 8 and 14, respectively. Judd et al, (2012) proposed a side-load rack system to economically compare against the rear-loading and densification system studied in Morey et al, (2010). Utilizing satellite storage locations for storage of switchgrass in South Central Virginia, the side-load rack system proved to be superior over a one-year period. A MILP optimization model was created minimizing total annual costs including equipment costs, size of production field, and processing capacity of the equipment. The side-load rack system had higher upfront costs but was coupled with lower annual costs, thus, providing to be a more economical solution. However, the model did not account for the variation in biomass availability as it was assumed to be supplied at a constant rate throughout the year.

By analyzing a given region's energy surplus-deficit curve and its respective biomass resources, the overall carbon footprint of a regional biomass supply chain was minimized through the use of the Regional Energy Clustering (REC) algorithm by means of a MILP optimization model (Lam and Klemes, 2010) considering fuel consumption, distance, biomass load per truck, and the carbon emissions factor for diesel trucks. This model proved the need of new road construction in Central Europe but was justified by analyzing the environmental and economic payback period, based on carbon tax and fuel consumption, respectively, against the existing transportation and energy infrastructure. Although environmental and economical decisions were applied to the supply chain design, the model is lacking a detailed cost analysis and does not account for variation in biomass availability.

The increase in the profit per unit of biofuels production from switchgrass is seen by incorporating strategic and tactical level decisions such as potential locations and operating schedules, respectively into the supply chain design (Zhu et al, 2011a). When corn stalk and wheat straw were added as potential biomass feedstocks, seasonality risks were alleviated by smoothing out the production of biofuels over the course of the year, therefore decreasing the risk of market saturation. Thus, an eventual increase of unit profit for biofuels will be seen (Zhu et al, 2011b).

A multi-criteria assessment methodology (Kumar et al, 2006) which integrates the economic, social, environmental, and technical factors to make the ranking of various alternatives to biomass collection and transportation systems possible was used to evaluate corn stover for the production of bioenergy. The metrics considered were biomass costs, quality of biomass, emissions during collection, energy consumption for supply chain operations, and maturity of supply system technologies. Using this framework, the authors compared 3 different transportation modes for corn stover: (1) truck, (2) rail, and (3) barge. Although this study incorporates both quantitative and qualitative metrics into the evaluation, the variation in monthly biomass availability was not considered.

Modeling techniques other than MILP modeling have been applied to model the biomass supply chain. For example, the IBSAL (Integrated Biomass Supply Analysis Logistics) model (Sokhansanj et al, 2006) is a highly detailed model to simulate the collection, storage, and transport operations for the supply of biomass to biorefinery considering the influence of weather, moisture content, and dry matter loss throughout the biomass supply chain. Even though various aspects of harvesting such as shredding, baling, and stacking as well as their respective completion date were taken into account, all biomass was transported to the biorefinery on the same day of the year. By doing so, a large amount of inventory is seen at the biorefinery which may lead to storage problems such as risk of fire, microbial degradation, and infestation.

Another approach, dynamic programming, has been applied (Gigler et al, 2002) to find the optimal biomass to fuel pathway by breaking the biomass into two states: (1) appearance and (2) quality. The state of appearance is defined as being influenced by handling actions while the quality state is influenced by processing, transportation and storage actions. By minimizing total costs, the optimal routes from biomass to fuel, defining which actor in the biomass supply chain should perform which handling actions and at which process conditions were found using willow biomass to supply a biorefinery as a case study.

The biomass supply chain frameworks presented earlier found that energy from biomass resources performed the same or better compared to their non-renewable counterparts. However, processing of the biomass to the desired product and the distribution of the products to market were not included in the decision support tools created. Also, the seasonal biomass availability was not accounted for in most models. For these reasons, a bioenergy supply chain accounting for variation in monthly biomass availability provides an excellent framework for strategic, tactical, and operational level decision making as it entails all stages of the biomass-to-bioenergy supply chain, from fields to markets.

2.2 Bioenergy Supply Chains

Biofuels have been categorized as first-, second-, and third-generation depending on the type of feedstock which they are derived from and the processing pathway for the production of such biofuels. First-generation biofuels are commercially produced using conventional technology from basic feedstock such as seeds, grains, or whole biomass typically used as a food commodity (Bringezu et al, 2009). Second-generation biofuels are produced from a variety of non-food sources using a variety of bio-chemical and thermo-chemical processes. Third-generation biofuels are usually not considered as fuels to the market due to the lack of production experience. The entire biofuels supply chain, from field to market, must be considered for the production of such biofuels. As defined by An et al, (2011) the biofuels supply chain, which is not limited to only biofuels but other biobased products as well, consists of three major components.

1) Upstream: defined earlier as the entire biomass supply chain (Rentizelas and Tolis, 2009)
2) Midstream: refining the biomass in some fashion to the desired end-use product(s).
3) Downstream: including storage of said product(s) and distribution to customers.

There has been much research for the production of ethanol and biodiesel from first generation feedstocks. Using Northern Italy as a case study for the production of ethanol from corn grain, supply chain costs were minimized through a MILP optimization model. The decisions in the model included the integrated management of key issues affecting the biofuels supply chain such as agricultural practice, biomass supplier allocation, production site locations and capacity, logistics distributions, and transportation system optimization (Zamboni et al, 2009a) assuming average daily biomass production throughout the year. The work was then extended to include a multi-objective environmental optimization where the total daily impact (TDI) of the biofuel supply chain was minimized considering costs and greenhouse gas (GHG) emissions. Two different scenarios were analyzed using this approach: (1) importing biofuels from outside sources, which delivered minimal costs, (2) the operation of the entire supply chain in Northern Italy which maximized environmental performance measured by GHG emissions (Zamboni, 2009b). Using the same case study, a new modeling approach was developed based on neighborhood representations to compare the work against Zamboni (2009a) for the years 2011 and 2020 forecasted to meet the EU biofuels target (Akgul et al, 2010). These studies integrate economical (Zamboni et al, 2009a), environmental (Zamboni et al, 2009b), future demand (Akgul et al, 2010), and uncertainty on biomass production cost and product selling price (Dal-Mas et al, 2011) while focusing on a single case study. Thus, providing various scenarios to aid policy makers and potential investors in the decision making process. However, monthly biomass availability and product demand were not considered therefore, providing to be an unrealistic model.

The use of sugarcane for the production of ethanol is common throughout the continent of South America. Due to the passing of published law 26093, Argentina plans to make use of its current sugarcane industry for the production of ethanol. Mele et al, (2011) developed a multi-objective MILP model to optimize the economic and environmental performance of the sugarcane to ethanol production chain. By maximizing the net-present value (NPV) and minimizing the total life-cycle emissions over a 4 year time frame, found through the use of Eco-indicator 99 and CML, an optimal sugarcane-to-ethanol supply chain configuration was found while taking the existing infrastructure into account. This study illustrates the trade-off that exists between the economic and environmental performance of the supply chain network. Nevertheless even though sugarcane is harvested multiple times a year, the variation in monthly sugarcane availability is not taken into account.

Considering rapeseed, sunflower, cotton, cynara, and soya for the production of biodiesel in Greece, a MILP model was developed to compare the economic feasibility of generating biodiesel within Greece or importing the fuel or biomass from outside sources (Papopostolou et al, 2011). Low-cost and high-cost scenarios were evaluated by means of government subsidies and no government subsidies, respectively. The case study considered 10% of total annual biomass production to avoid the fuel vs. food debate to meet 10% of diesel demand. The low-cost scenario imported biomass to meet the demand, whereas, the high-cost scenario imported biomass and 13% of the total biofuels to meet the 10% demand. The case study illustrates the potential need of government subsidies to meet biofuel demand or mandates.

First-generation biofuels appear unsustainable due to the potential stress on food commodities from their production (Naik et al, 2010). For this reason second-generation biofuels have gained much attention. For example, through evaluation of logging residues, straw, and short rotational woody crops, as well as diesel demand in Northern Germany, a MILP optimization model has been developed for the selection of an integrated location, capacity, and technology planning for the second generation synthetic biofuels by maximizing the NPV over a 20 year period (Walther et al, 2012). Other work consist of the evaluation of barley straw, corn stover, winter wheat straw, spring wheat straw, and oats residue for the production of ethanol in a 9-state region in the Midwestern United States using a MILP model to maximize NPV over a 20 year period. Considering existing ethanol infrastructure in this area and the ethanol tax credit, the optimal locations and capacity were simultaneously selected with biomass harvest and distribution (Marvin et al, 2012). Huang et al, (2009) considered eight waste biomass resources for the production of ethanol utilizing a MILP model to minimize total supply chain costs considering 28 candidate refinery locations so that in-state ethanol production meets 75% of the state's biofuel consumption by 2050. From these existing biomass waste streams, a new bioethanol supply chain configuration was found to be sustained through multiple studies in the state of California at a cost of $1.10 per gallon (Huang et al, 2009). Even though the models mentioned here considered capital cost through discounted cash flows over a long period of time, biomass availability and product demand is based on an annual basis. Therefore, by not accounting for market fluctuations throughout the year, the model could have unrealistic outputs.

Based on an S-shaped trajectory hydrogen demand curve over a 50 year period in Great Britain, a simulation based approach was adopted to design and operate a deterministic, steady-state hydrogen supply chain network. Almansoori and Shah, (2009) considered the availability of renewable and non-renewable resources such as biomass, coal, natural gas, and petroleum coke, to minimize total daily costs of the hydrogen supply chain. The long-term planning approach led to a phased infrastructure starting with small plants then continuing with the expansion of such plants along with the opening of new larger plants to meet the increasing demand.

Tittman et al, (2010) used a spatially techno-economic Biomass Siting Model (BSM) to determine facility siting and size, conversion technology, feedstock profile, and the respective supply chain configuration for the state of California in 2015. By coupling a Geographic Information System (GIS) and a MILP optimization model to maximize profit, the BSM model considered different scenarios based on a price range of $2.20 - $4.00 per gallon of gasoline equivalent utilizing 15 feedstocks transported by truck, rail or barge for the production of gasoline, biodiesel, and electricity. This work was then extended to assess the potential biofuels supply across the Western United States from agricultural, forest, and urban residues as well as energy crops (Parker et al, 2010) proving 15% of current regional liquid transportation fuels could be met at a cost of $19.6/GJ. Tittman et al, (2010) and Parker et al, (2010) proved that energy from biomass resources can not only compete against conventional energy resources but also can be scaled appropriately to meet future demand. However, monthly variation in biomass availability and product demand was not accounted for, nor were costs related to labor, supervisor, maintenance, and overhead costs at the biorefinery.

The economic potential and infrastructure requirements of hydrogen production from rice straw and wheat straw in Northern California were evaluated utilizing a mixed-integer non-linear program (MINLP) optimization model (Parker et al, 2008). The size, location, and allocation of biomass and feedstocks were determined by maximizing profit over a 15 year time frame. Four demand scenarios were investigated corresponding to 1%, 10%, 25%, and 50% of current light duty vehicles in Northern California. Through the model, the available biomass feedstocks can fuel approximately 40% of the current light-duty vehicle fleet at costs similar to producing hydrogen from natural gas.

A MILP model was created by Kim et al, (2011a) to decide the fuel conversion technology, capacity, amount of biomass, intermediates, and final products, biomass location, market locations, and the different types of pre-processing plants using woody biomass for the production of gasoline and biodiesel in 9 states in Southeastern USA. By maximizing overall profit, a distributed and centralized supply chains were compared in which the distributed network proved to be most profitable. A sensitivity analysis was then conducted using the 14 main parameters affecting the biofuels supply chain (Kim et al, 2011b). Over long distances, a distributed supply chain (pre-processing located closer to biomass sources) was again proved to be more economical by using disjunctive models to yield convex relationships between capital costs and biorefinery capacity (Bowling et al, 2011).

Through an extensive literature review (An et al, 2011a) it was found that no available models exist to integrate the strategic, tactical, and operational decisions in conventional fossil fuels and biofuels supply chain management. In one of the very few studies, both strategic (biorefinery locations) and tactical (quarterly amount of biomass) level decisions were included in upstream and downstream echelons over multiple time period using switchgrass for the production of ethanol in Central Texas (An et al, 2011b). Through this methodology, the authors proved that when tactical and strategic decisions are integrated into the supply chain design, overall higher profitability can be achieved.

The profitability of bioenergy as well as biomass supply risk mitigation appear to be superior when considering a multi-feedstock approach compared to a single-feedstock (Rentizelas et al, 2009; Zhu et al, 2011b; Huang et al, 2010). The multi-feedstock approach alleviates potential availability risks associated with a single feedstock such as, crop infestation, growing degree days, rain, microbial decay, and yield. Fluctuating market conditions affecting the pricing of products produced are also a major concern for the efficient management of a biorefinery (Yun et al, 2009). For these reasons, an integrated biorefinery is a viable conversion technology as it provides the flexible means for producing a wide range of fuels and chemicals from a large resource base.

2.3 Integrated Biorefinery

By diversifying products as well as the procurement of raw materials, an integrated biorefinery is seen as a flexible manufacturing process to provide a sustainable supply of products such as biofuels, bulk and fine chemicals, hydrogen, and electricity (Yun et al, 2009; Werpy et al, 2004). By combining thermochemical and biochemical conversion technologies, more flexibility in product generation as well as lower overall costs is anticipated through the integrated biorefinery approach (Naik et al, 2010). Due to the ability to produce a large slate of products from various resources, integrated biorefining is seen as a suitable platform for generating bioproducts from lignocelluloses (Huang et al, 2009) due to pre-existing infrastructure as well as the combination of lignocellulose resources with conventional fossil fuel resources such as coal and natural gas (Baliban et al, 2011). Attempts have been made to optimize the biomass-to-product pathway utilizing an integrated biorefinery approach (Huang et al, 2009; Tay et al, 2011).

To fully take advantage of an integrated biorefinery potential, strategic, tactical, and operational level supply chain decisions from the procurement of raw materials to the allocation of products to market must be coupled with respective processing decisions. When combining such decisions into one single model, complexity increases exponentially. To encompass both decision aspects, the modeling of an integrated biorefinery supply chain must be broken down into two models: (1) supply chain and (2) process. Collaboration and communication between the two models must be possible to sufficiently incorporate strategic, tactical, and potentially operational level decisions into the integrated biorefinery supply chain design.

2.4 Collaborative Work

Minimal work has been conducted addressing collaboration between supply chain and processing models for integrated biorefining. Elia et al, (2011) analyzed the national energy supply network utilizing a hybrid coal, biomass, and natural gas to liquid (CBGTL) plant conversion technology from earlier work (Baliban et al, 2010; Elia et al, 2010). Three plant sizes for the distribution of liquid transportation fuels were evaluated and their respective locations were identified to meet the nation's liquid transportation fuel needs. Using process simulation software, ASPEN Plus, a total of 270 process simulations were carried out for each combination of coal, biomass, natural gas type, and plant size. From this, the overall national supply chain configuration was found by minimizing total supply chain costs through a MILP model. Based on various scenarios, the network found proved to be capable of supplying the transportation fuels demands of the country at a cost of $76-$113 per barrel of crude oil equivalent. In a separate study, a biodiesel plant with a production capacity of 8,000 tons per year was evaluated to identify suitable technologies for waste reduction, energy recovery, and product quality improvement. Overall results were found by means of combining process results of various waste reduction technologies from process simulation software, HYSYS, along with those found through the sustainability assessment conducted via goal programming (Liu and Huang, 2012).

2.5 Summary

A substantial amount of research has been conducted with regards to the transportation, storage, and processing of biomass resources to desired products. Considering strategic level decisions in the supply chain design, many researchers were able to prove that energy derived from biomass resources performed at the same level or better economically when compared against non-renewable resources such as coal, natural gas, and petroleum. When combining strategic level and tactical level decisions into the supply chain design as well as utilizing a multi-feedstock approach, biofuels were either able to compete with or outperform fuels created from conventional resources. Integrated biorefining proves to be a flexible manufacturing process to mitigate risks associated with creating energy, fuels, and chemicals from biomass as it provides a means for producing a wide range of products from a large renewable and non-renewable resource base. With all this in mind, there has yet to be a decision-support tool to incorporate strategic, tactical, and operational decisions levels into the supply chain design of an integrated biorefinery.

3 METHODOLOGY

The objective of this research is to develop a framework for the supply chain problem for two different conversion technologies, integrated biorefining and fermentation, while considering varying biomass monthly availability and product demand. The purpose of this framework is to not only optimize the allocation of a biorefinery's feedstock inputs, product outputs, as well as selecting the location of a biorefinery and its respective supply chain design but also to answer many questions about the supply chain design through a post-optimality analysis. Multiple steps are necessary during the process of developing such a framework as it is structured into three stages: (1) definition of problem scope, (2) model development, and (3) optimization and analysis. Figure 3-1 below presents the steps in each stage of the framework. The following sections of this chapter will discuss in detail the specifics relating to each stage.

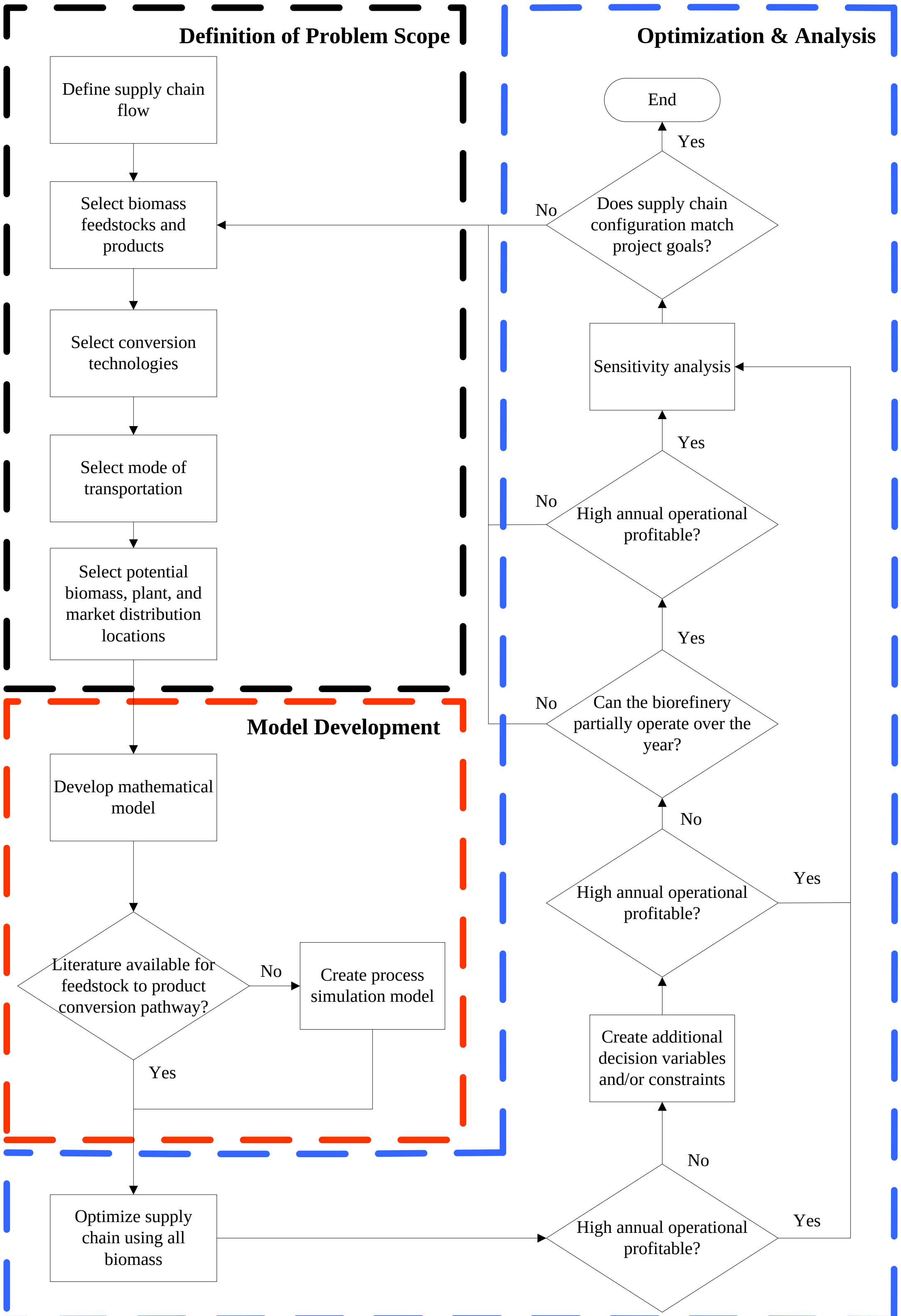


Figure 3-1: Framework development steps

3.1 Definition of Problem Scope

First, the potential supply chain configuration must be defined by: (1) defining the material flow through the supply chain, (2) identifying the bioenergy products to be created from the available biomass in a given region, (3) selecting conversion technologies to create said products, (4) selecting the transportation mode, and (5) selecting potential biomass, biorefinery, and market distribution locations. A simple schematic of the flow of material through the supply chain from field to market is shown in Fig. 3-2. It is assumed the biomass feedstock at the biomass locations are in suitable form to be transported to the biorefinery locations. The biomass is then converted into the final product form at the biorefinery to subsequently be transported to the product locations via truck, pipeline, or the electric grid. It is also assumed that trucks arrive full at the biorefinery or product location and are returned empty to respective initial locations to be loaded with either feedstock or product.

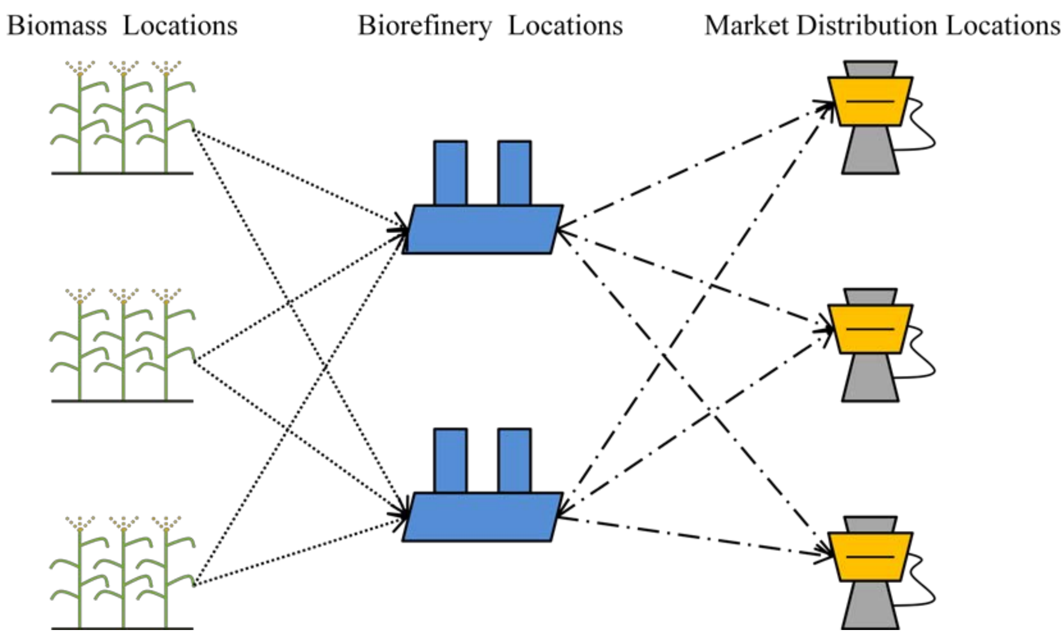


Figure 3-2: Defining supply chain flow

In order not to compete with food crops, the selected biomass feedstocks to be considered are poultry litter, corn stover, forest residue, and winter wheat straw. Products to be created from these biomass resources are ethanol, gasoline, diesel, residual fuel oil, natural gas, and electricity. As pointed out in the literature review, integrated biorefining seems to have advantageous process capabilities when compared to conventional conversion technology due to the wide range of products created from various feedstocks. Therefore, integrated biorefining is chosen as a conversion technology to be compared against fermentation, a conventional technology, to better understand the difference in supply chain performance. The integrated biorefining scenario will consider utilizing chicken litter, corn stover, and forest residue for the production of gasoline, diesel, bitumen and waxes, natural gas, and electricity. The fermentation involves using corn stover and winter wheat straw for the production of ethanol. Given the region's total biomass availability and market product demand, the potential biomass, biorefinery, and market distribution locations are selected based on spatial analysis of biomass and population density.

3.2 Model Development

3.2.1 Model Assumptions

The assumptions made in the model development stages are listed below.

1) The specific conversion technology for integrated biorefining is Gasification, Water-Gas Shift, and Fischer Tropsch Synthesis.
2) The specific conversion technology for fermentation is Dilute-Acid Pretreatment, Saccharification and Fermentation.
3) Products created for the integrated biorefinery consist of electricity from hydrogen, residual fuel oil, gasoline, diesel, and natural gas.
4) The only product created via fermentation is ethanol.
5) Biomass feedstocks, gasoline and diesel are transported to and from the biorefinery by truck.
6) Natural gas is transported to market location via pipeline.
7) There is no need for construction of natural gas pipelines or additional electric grid sections in the given region (they are assumed to exist).
8) Biomass feedstocks and products are available in suitable form to be shipped to their downstream supply chain location.
9) There is no limitation of the number of trucks to be used.
10) Surplus biomass at biomass locations slowly degrades if not used.
11) Electric line loss occurs due to grid inefficiencies.
12) Capital costs are not included in the initial optimization model.
13) If trucks are filled partially with biomass feedstock or product, the amount transported will be accounted for but the truck will be assumed full for diesel cost purposes.
14) Trucks return to biomass feedstock and plant locations empty.
15) Truck speed is constant.
16) The cost of purchasing the biomass feedstock includes all steps related to the collection and transportation of said biomass to the biomass locations.

17) Any electricity created at the biorefinery will be sold to the grid and is not designed for in-house use (safety is the main driver here due to a constant need of electricity to run the automated equipment in the remainder of the integrated biorefinery).
18) Demand of products is constant throughout the month.
19) Corn stover and winter wheat straw is to be harvested at the same time as their respective grains.
20) Operational planning for the integrated biorefinery begins in August while that for the fermentation plant starts in June (due to the harvest of corn stover and winter wheat straw, respectively).

3.2.2 Mathematical Model

A mixed integer linear program (MILP) was formulated to serve as the mathematical model to maximize total profit of a biorefinery dependent on monthly biomass feedstock availability, conversion technology limitations, and market demand constraints. Costs to be considered are biomass purchasing cost, utility cost, labor cost, supervisor cost, overhead cost, transportation cost and respective diesel cost to transport biomass feedstocks and products. The sales of the created products and the location of consumption have been based on population and market demand of each individual product. The MILP optimization model does have constraints which will need to be fulfilled. Any products created at the biorefinery should be sold to market without exceeding demand so that the market does not become oversaturated, thus, driving down the price of the product and subsequent overall profitability. The amount of biomass to create such products should also not exceed availability in the same region so that importing biomass is avoided, which would increase costs and decrease profitability. Even though the biomass and market distribution locations may vary on a monthly basis, depending on supply and demand, the biorefinery should not as it will be a constant fixture throughout the planning period.

The biorefinery supply chain can be broken down into three sections: biomass source locations (i), potential biorefinery locations (j), and market distribution locations (k). The strategic supply chain design accounts for monthly feedstock availability as it is a parameter (B") depending on the new supply (B) and the aged supply (B") for each month (m), feedstock (f) and feedstock location (i). Other biomass parameters include biomass purchase cost (BC_f) and the amount of biomass shipped in a truckload (TM_f). Such parameters with respect to the products are inputs in the model as well.

Given the parameters of the problem, the decisions variables included in the model are described below:

- P_j: the selection of a biorefinery at location (j).
- X_{fijm}: the amount of feedstock (f) to be transported from biomass feedstock location (i) to biorefinery location (j) in month (m).
- Y_{pjkm}: the amount of product (p) to be transported from biorefinery location (j) to market distribution location (k) in month (m).

Table 3-1 represents the notations used in the development of the mathematical model.

Table 3-1: Notations

Notation	**Description**
TM	*Truck mass*
TM'	*Biomass truck capacity*
TM''	*Product truck capacity*
ρ	*Density*
s	*Truck speed*
d	*Distance*
k	*Truck diesel consumption conversion*
T	*Number of trucks*
c	*Labor hours needed conversion*
c'	*Ethanol produced conversion*
B	*New supply of biomass*
B'	*Aged biomass*
B''	*Total biomass availability*
BN	*Biomass needed*
E	*Biomass feedstock erosion factor*
P	*Product supply*
P'	*Product demand*
L	*Product loss during transportation*
R	*Biomass land rent cost*
BC	*Biomass purchasing cost*
BC'	*Biomass inventory cost*

Table 3-1, Continued

BC''	*Biomass transportation truck cost*
BC'''	*Biomass transportation diesel cost*
BTC	*Biomass truck distance dependent cost*
BTC'	*Biomass truck time dependent cost*
OC	*Operating cost*
COOL	*Biorefinery cooling cost*
HEAT	*Biorefinery heating cost*
ELEC	*Biorefinery electricity cost*
LC	*Labor cost*
LC'	*Hourly labor cost*
MC	*Maintenance cost*
MC'	*Maintenance cost conversion*
SC	*Supervisor cost*
OVC	*Overhead cost*
PC	*Product transportation cost*
PC'	*Product transportation diesel cost*
PTC	*Product truck distance dependent cost*
PTC'	*Product truck time dependent cost*
DP	*Diesel price*
BP	*Biomass purchase price*
PP	*Product selling price*
X	*Amount of biomass feedstock*
Y	*Amount of product*
P	*Plant open*
f	*Subscript - corresponds to biomass feedstock*
p	*Subscript - corresponds to product*
i	*Subscript - corresponds to biomass location*
j	*Subscript - corresponds to plant location*
k	*Subscript - corresponds to product location*
m	*Subscript - corresponds to month*

The annual profit is to be maximized through the optimization model determined based on revenue from the sale of products while considering the associated costs of delivering said products to market feedstock and operational cost as well as inventory cost as show below.

$$Total\ Profit = \sum_{m=1}^{12} (Sales_m - \ Cost_m) \tag{3.1}$$

The revenue of the sales for each month depends on the products created in that month (P_{pm}) and the price of the product (PP_p).

$$Sales_m = \sum_{p=1}^{P} P_{pm}\ PP_p \tag{3.2}$$

The cost associated with the biorefinery supply chain comprises of monthly biomass purchasing cost (BC_m), inventory cost (BC'_m), biomass transportation cost (BC''_m), the cost of diesel to transport the biomass (BC'''_m), operating cost (OC_m), product transportation cost (PC_m), and product transportation diesel cost (PC'_m). Therefore, the cost for any given month m;

$$Cost_m = BC_m + \ BC'_m + BC''_m + BC'''_m + OC_m + PC_m + PC'_m \tag{3.3}$$

The biomass purchasing cost (BC_m) depends on the price of the biomass (BP_f) and the amount consumed for the month for each location (X_{fijm}). The cost here reflects the cost of all the steps needed to provide the biomass in suitable form to be shipped from biomass location to the biorefinery.

$$BC_m = \sum_{f=1}^{F} \sum_{i=1}^{I} \sum_{j=1}^{J} X_{fijm}\ BP_f \tag{3.4}$$

The inventory taken from the biomass location (X_{fijm}) is taken into account for in determining the inventory cost (BC'_m) as land rent (R) will be charged.

$$BC'_m = \sum_{f=1}^{F} \sum_{i=1}^{I} \sum_{j=1}^{J} X_{fijm}\ \ R \tag{3.5}$$

The biomass transportation cost (BC''_m) is a function of the number of trucks (T_{fijm}), distance travelled (d_{ij}), distance dependent cost (BTC) and the time dependent cost of transportation (BTC'). The truck speed (s) has been assumed to be constant. Note that the biomass transportation cost (BC''_m) only includes costs related to the maintenance of the truck as well as the cost of the driver. The truck will make two trips, one from the biorefinery to the biomass location and then from the biomass location back to the biorefinery location.

$$BC''_m = \sum_{f=1}^{F}\sum_{i=1}^{I}\sum_{j=1}^{J} 2T_{fijm}\, d_{ij}\, (BTC + \frac{BTC'}{s}) \tag{3.6}$$

The energy consumption conversion factor (*k*), described later in this section is then used for the calculation of biomass transportation diesel cost (BC'''_m) based on the number of trucks used for biomass transport in the month (T_{fijm}), distance travelled (d_{ij}), truck mass (TM), biomass truck mass (TM'_f), and the price of diesel (DP). Note that the mass of the biomass in the truck (TM'_f) is the mass of the biomass feedstock that is added to the truck without exceeding the road capacity limits. The truck will make two trips, one full from biomass location to biorefinery location, and one empty from biorefinery location to biomass location.

$$BC'''_m = \sum_{f=1}^{F}\sum_{i=1}^{I}\sum_{j=1}^{J} k\, T_{fijm}\, d_{ij} \left(2TM + TM'_f\right) DP \tag{3.7}$$

The operating costs (OC_m) for the biorefinery consists of seven different costs: (1) cooling costs ($COOL_m$) considering any cooling water needed at the biorefinery, (2) heat costs ($HEAT_m$) factoring any steam usage and (3) electricity ($ELEC_m$) to run any automated equipment at the biorefinery such as pumps, compressors, and chillers, (4) labor costs (LC_m) for manpower needed at the biorefinery, (5) supervisor costs (SC_m) of respective manpower, (6) maintenance costs (MC_m), and (7) overhead costs (OVC_m) relating to management team, engineers, lawyers, and other support staff. Even though the integrated biorefinery generates electricity from hydrogen, it is assumed that the entire quantity will be sold to the grid and not used in-house. This is realistic given the safety concerns that could arise if an intermittent supply of electricity is used; disruption in this supply may have detrimental effects. Therefore, electricity ($ELEC_m$) will be bought from the readily available electric grid.

$$OC_m = ELEC_m + COOL_m + HEAT_m + LC_m + SC_m + MC_m + OVC_m \tag{3.8}$$

The labor costs (LC_m) is dependent on the amount of products created (PS_{pjm}), hourly cost to pay an employee (LC'), as well as conversion factors (c) and the density of the product (ρ_p). The conversion factor (c), relates to the amount of labor needed per amount of product created. Luckily over the years, Peters et al (2003), have built a large database on the labor costs associated with producing energy, fuels, and chemicals in the United States.

$$LC_m = \sum_{p=1}^{P} cLC'\rho_p PS_{pjm} \quad \forall\, p, j, m \tag{3.9}$$

Supervisor costs (SC_m) at the biorefinery is assumed to be 15% of the monthly labor costs (LC_m).

$$SC_m = 0.15LC_m \quad \forall\, m \tag{3.10}$$

For the production of ethanol ($p = 6$), the maintenance costs (MC_m) is dependent on the amount of products created (PS_{pjm}) and the maintenance cost conversion (MC'), which is dependent on the size of the biorefinery.

$$MC_m = MC'PS_{pjm} \quad \forall\, m, \&\, p = 6 \tag{3.11}$$

The monthly overhead costs (OVC_m) is assumed to be 50% of the sum of the labor costs (LC_m), supervisor costs (SC_m), and maintenance costs (MC_m).

$$OVC_m = 0.5(LC_m + SC_m + MC_m) \quad \forall\, m \tag{3.12}$$

For the production of ethanol ($p = 6$), a simple conversion factor (c') will be used to determine the amount of product supplied (PS_{pjm}) based on the amount of biomass transported to the biorefinery (X_{fijm}).

$$PS_{pjm} = \sum_{f=1}^{F} \sum_{i=1}^{I} \sum_{j=1}^{J} c'X_{fijm} \quad \forall\, m\ \&\ p = 6 \tag{3.13}$$

The product transportation cost (PC_m) is also calculated in a similar way as with the biomass transportation cost (BC''_m)) as a function of product distance dependent cost (PTC), time dependent cost (PTC'), distance travelled (d_{jk}), speed (s) and number of trucks for product transport (T_{pjkm}).

$$PC_m = \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K} 2T_{pjkm}\, d_{jk}\, (PTC + sPTC') \tag{3.14}$$

As with the biomass transportation diesel costs (BC'''_m), the product transportation diesel cost (PC'_m) is calculated in a similar manner.

$$PC'_m = \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K} k\, T_{pjkm}\, d_{jk} \left(2TM + TM''_p\right) DP \tag{3.15}$$

The number of trucks needed (T_{fijm}) to transport the biomass feedstock (X_{fijm}) from biomass location (i) to biorefinery location (j) depends on the amount of biomass to be transported (X_{fijm}) as well as the biomass truck capacity (TM'_f).

$$\frac{X_{fijm}}{TM'_f} = T_{fijm} \quad \forall\, f, i, j, m \tag{3.16}$$

Given the density (ρ_p) of gasoline, diesel, and residual fuel oil, the number of trucks needed to transport these products (T_{pjkm}) is based on the amount of product to be shipped (Y_{pjkm}) and the truck capacity of the product (TM''_f).

$$\frac{Y_{pjkm}\, \rho_p}{2{,}000\, TM''_f} = T_{pjkm} \quad \forall\, f, j, k, m \tag{3.17}$$

The following constraints will need to be satisfied for the MILP optimization model. The constraints related to the biomass feedstocks will be the same for the integrated biorefining and fermentation scenarios, whereas the constraints for the different products will vary due to some inventory being held at the biorefinery. For this reason, the following product numbers will be referenced in the constraints.

1) Electricity

2) Gasoline
3) Diesel
4) Natural Gas
5) Residual Fuel Oil
6) Ethanol

Of the potential biorefinery locations (j), only one is opened.

$$\sum_{j=1}^{J} P_j = 1 \tag{3.18}$$

The amount of biomass feedstock (X_{fijm}) to be transported from each biomass location (i) to biorefinery location (j) should not exceed the total amount of biomass available (B''_{fim}) at the respective location for each type of biomass. Therefore;

$$\sum_{j=1}^{J} X_{fijm} \leq B''_{fim} \quad \forall f, i, m \tag{3.19}$$

For the first month of the planning period, the total amount of biomass feedstock available (B''_{fim}) for each feedstock type at each biomass location (i) is equal to the new supply (B_{fim})

$$B_{fim} = B''_{fim} \quad \forall f, i, \& \; m = 1 \tag{3.20}$$

For the remaining months of the year, the surplus of biomass or aged biomass (B'_{fim}) will be considered along with the new supply (B_{fim}) for the total available amount (B''_{fim}).

$$B_{fim} + B'_{fim} = B''_{fim} \quad \forall f, i, \& \; m = 2..12 \tag{3.21}$$

The amount of aged biomass (B'_{fim}) at biomass location (i) is solely dependent on the amount shipped in the prior month (X_{fijm-1}), the total amount in that month (B''_{fim-1}) and the degradation or erosion factor (E_f). Therefore;

$$E_f\left(B''_{fim-1} - \sum_{j=1}^{J} X_{fijm-1}\right) = B'_{fim} \quad \forall\, f, i, \& \, m = 2..12 \tag{3.22}$$

For all months, the amount of biomass transported (X_{fijm}) is the amount that is needed at the biorefinery (BN_{fm}).

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{fijm} = BN_{fm} \quad \forall f, m \tag{3.23}$$

The amount of product to be shipped in a month (Y_{pjkm}) should be equal to the amount created in that month (PS_{pjm}).

$$\sum_{j=1}^{J}\sum_{k=1}^{K} Y_{pjkm} = PS_{pjm} \quad \forall\, m, p \tag{3.24}$$

The amount of product transported (Y_{pjkm}) to the product location (k) should also not exceed the monthly demand (PD_{pkm}) for that product.

$$\sum_{j=1}^{J} Y_{pjkm} \leq PD_{pkm} \quad \forall p, k, m \tag{3.25}$$

The big M method has been applied with the intention of not sending biomass feedstock to a biorefinery location which is not opened as well as sending product to market distribution centers from a closed location.

$$\sum_{f=1}^{F}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} X_{fijm} \leq MP_j \quad \forall j \tag{3.26}$$

$$\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} Y_{pjkm} \leq MP_j \quad \forall j \tag{3.27}$$

A non-negativity constraint has been added for the amount of products (Y_{pjkm}) and biomass feedstock (X_{fijm}) to be transported.

$$Y_{pjkm}, X_{fijm} \geq 0 \tag{3.28}$$

A binary constraint has been placed on the plant location (P_j) to open the plant at location (j) for that year.

$$P_j = binary \tag{3.29}$$

3.2.3 Diesel Consumption Calculation

It has been determined that all biomass feedstocks and a couple of the products will be transported from their source location to the downstream supply location via truck. For this reason, a simple methodology has been created to calculate the amount of diesel needed to transport the said biomass feedstocks and products. By assuming energy losses due to (1) combustion and (2) friction, one can calculate the amount of diesel needed to transport a ton of material over a given distance. For this, it has been assumed 25% of the energy output from the combustion process (E_{engine}) is lost due to frictional losses from engine to wheel, while 50% of the energy from the diesel (E_{diesel}) is lost during the combustion process. Therefore, the efficiency of the engine output to wheel ($\eta_{friction}$) and diesel to engine (η_{engine}) is 75% and 50%, respectively. Given the energy density of diesel (μ_{diesel}) one then can calculate the amount of energy needed at the wheel (E_{wheel}) from diesel (E_{diesel}). Given the amount of energy from diesel needed (E_{diesel}), the amount of diesel can then be calculated using the energy density of diesel (μ_{diesel}) as provided by Thomas and Keller (2003). To provide 1 MJ of energy at the wheel, 0.0207 gallons of diesel are needed.

$$E_{engine} = \eta_{engine} E_{diesel} \tag{3.30}$$

$$E_{wheel} = \eta_{friction} E_{engine} \tag{3.31}$$

$$E_{wheel} = \eta_{friction} E_{engine} \tag{3.32}$$

$$E_{wheel} = \eta_{friction} \; \eta_{engine} E_{diesel} \tag{3.33}$$

$$E_{diesel} = \frac{E_{wheel}}{\eta_{friction} \; \eta_{engine}} \tag{3.34}$$

$$Diesel\ (gall) = \frac{E_{diesel}}{\mu_{diesel}} \tag{3.35}$$

$$E_{diesel} = \frac{1\ MJ}{(0.75)\ (0.5)}$$

$$E_{diesel} = \frac{1\ MJ}{(0.75)\ (0.5)}$$

$$Diesel\ (gall) = \frac{2.67\ MJ}{128.705\ ^{MJ}/_{gall}}$$

$$Diesel\ (gall) = 0.0207$$

Using the methodology described above and Eqns. 3.30-3.35, the amount of diesel can be easily calculated given the wheel energy (E_{wheel}). Since the frictional losses have already been taken into account, the wheel energy will just need to overcome the force of gravity. Therefore;

$$E_{wheel} = Work = Force * distance = mass * gravity * distance \tag{3.36}$$

By a simple unit conversion the amount of energy needed to transport one ton over a mile can be calculated.

$$E_{wheel} = 14.3\ MJ/ton - mi$$

By using Eqn. 3.36 above, as well as the given the frictional efficiency ($\eta_{friction}$), engine efficiency (η_{engine}), and the energy density of diesel (μ_{diesel}), the amount of diesel needed can be determined as shown in Eqn. 3.37 below.

$$Diesel\ (gall) = \frac{E_{wheel}}{\eta_{friction}\ \eta_{engine}\ \mu_{diesel}} \tag{3.37}$$

$$Diesel\ (gall) = \frac{14.3\ MJ/ton - mi}{(0.75)(0.5)128.705\ ^{MJ}/_{gall}}$$

$$Diesel = 0.2963\ gall/ton - mi$$

Using the methodology described here, the amount of diesel is easily calculated based on the amount of biomass to be transported and the distance travelled, as it will be an input into the MILP optimization model. With regards to other model inputs, if literature did not exist for the biomass feedstock to product pathway, an ASPEN process simulation model was created to provide inputs into the MILP optimization model such as monthly with regards to heating ($HEAT_m$) , cooling ($COOL_m$), and electricity costs ($ELEC_m$) of the biorefinery as well as feedstock (f) requirements needed to create the desired product portfolio. Due to a limited number of iterations and the Economic Optimizer feature being limited to liquids and gases (biomass, bitumen and waxes are in solid form) the ASPEN process models were ran by minimizing total utility costs by setting a constraint on the range of feedstock to be used. On the other hand, if literature did exist for the chosen conversion technology (as the case with fermentation), then costs associated to processing were used as inputs into the MILP optimization model.

3.3 Optimization and Analysis

An initial analysis was performed using all the biomass so that a baseline is established for monthly supply chain performance. If the initial supply chain configuration does not have a high annual operational profit, additional decision variables and/or constraints were added to the MILP optimization model. Potential decisions include the which conversion technology to use, which biomass feedstocks to be shipped, or which products may be better to ship via rail, pipeline, or barge. The plant size can be added as a decision variable to the optimization model for the fermentation scenario due to readily available literature, whereas this did not exist for the integrated biorefining scenario as limitations were seen with the Economic Optimizer feature and a limited number of iterations. If the size of the plant cannot be included in the MILP optimization model due to the complexity of handling multiple feedstock and products in various physical states - solids, liquids, and gases - a range for the amount of feedstock to be used can be included in the ASPEN process model. The resulting outputs from the process model are then plugged into the MILP optimization model. If the new supply chain design is still not operational profitable over a year or even over a given time frame within that year, different feedstocks and/or conversion technologies must be assessed for a feasible supply chain configuration. A sensitivity analysis was then conducted to analyze the robustness of the various supply chain configurations to analyze whether the supply chain design matched with project goals. The model has been created to capture the supply chain economic performance on a monthly basis. A summary of objective function, parameters, and constraints of the MILP optimization model is provided below.

Objective Function: Maximize Total Profit

$$Total\ Profit = \sum_{m=1}^{12} (Sales_m - Cost_m) \tag{3.1}$$

Parameters:

$$Sales_m = \sum_{p=1}^{P} P_{pm}\, PP_p \tag{3.2}$$

$$Cost_m = BC_m + BC'_m + BC''_m + BC'''_m + OC_m + PC_m + PC'_m \tag{3.3}$$

$$BC_m = \sum_{f=1}^{F}\sum_{i=1}^{I}\sum_{j=1}^{J} X_{fijm}\, BP_f \tag{3.4}$$

$$BC'_m = \sum_{f=1}^{F}\sum_{i=1}^{I}\sum_{j=1}^{J} X_{fijm}\ R \tag{3.5}$$

$$BC''_m = \sum_{f=1}^{F}\sum_{i=1}^{I}\sum_{j=1}^{J} 2T_{fijm}\, d_{ij}\, (BTC + \frac{BTC'}{s}) \tag{3.6}$$

$$BC'''_m = \sum_{f=1}^{F}\sum_{i=1}^{I}\sum_{j=1}^{J} k\, T_{fijm}\, d_{ij} \left(2TM + TM'_f\right) DP \tag{3.7}$$

$$OC_m = ELEC_m + COOL_m + HEAT_m + LC_m + SC_m + MC_m + OVC_m \tag{3.8}$$

$$LC_m = \sum_{p=1}^{P} cLC'\rho_p PS_{pjm} \quad \forall\, p, j, m \tag{3.9}$$

$$SC_m = 0.15LC_m \quad \forall\, m \tag{3.10}$$

$$MC_m = MC'PS_{pjm} \quad \forall\, m, \&\, p = 6 \tag{3.11}$$

$$OVC_m = 0.5(LC_m + SC_m + MC_m) \quad \forall\, m \tag{3.12}$$

$$PS_{pjm} = \sum_{f=1}^{F}\sum_{i=1}^{I}\sum_{j=1}^{J} c'X_{fijm} \quad \forall\, m\ \&\ p = 6 \tag{3.13}$$

$$PC_m = \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K} 2T_{pjkm}\, d_{jk}\, (PTC + sPTC'\ ) \tag{3.14}$$

$$PC'_m = \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K} k\, T_{pjkm}\, d_{jk} \left(2TM + TM''_p\right) DP \tag{3.15}$$

$$\frac{X_{fijm}}{TM'_f} = T_{fijm} \quad \forall\, f, i, j, m \tag{3.16}$$

$$\frac{Y_{pjkm}\,\rho_p}{2{,}000\,TM''_f} = T_{pjkm} \quad \forall\, f, j, k, m \tag{3.17}$$

Subject to:

$$\sum_{j=1}^{J} P_j = 1 \tag{3.18}$$

$$\sum_{j=1}^{J} X_{fijm} \leq B''_{fim} \quad \forall\, f, i, m \tag{3.19}$$

$$B_{fim} = B''_{fim} \quad \forall\, f, i, m = 1 \tag{3.20}$$

$$B_{fim} + B'_{fim} = B''_{fim} \quad \forall\, f, i, \&\, m = 2..12 \tag{3.21}$$

$$E_f\left(B''_{fim-1} - \sum_{j=1}^{J} X_{fijm-1}\right) = B'_{fim} \quad \forall\, f, i, \&\, m = 2..12 \tag{3.22}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{fijm} = BN_{fm} \quad \forall f, m \tag{3.23}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} Y_{pjkm} = PS_{pjm} \quad \forall\, m, p \tag{3.24}$$

$$\sum_{j=1}^{J} Y_{pjkm} \leq PD_{pkm} \quad \forall p, k, m \tag{3.25}$$

$$\sum_{f=1}^{F}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} X_{fijm} \leq MP_j \quad \forall j \tag{3.26}$$

$$\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} Y_{pjkm} \leq MP_j \quad \forall j \tag{3.27}$$

$$Y_{pjkm}, X_{fijm} \geq 0 \tag{3.28}$$

$$P_j = binary \tag{3.29}$$

A holistic analysis of the potential for biobased fuels and chemicals is generated by combining and analyzing the various supply chains configurations collectively. A case study demonstrating this approach is presented in Chapter 4. Following a description of the conversion technologies in Chapter 5, the results from the study are further analyzed in Chapter 6 and Chapter 7 for the integrated biorefinery and fermentation scenarios, respectively.

4 CASE STUDY

The Jackson Purchase Region in Western Kentucky has been chosen as a case study to validate the framework presented in Chapter 2. Gasoline, diesel, electricity, residual fuel oil, natural gas, and ethanol are to be created from poultry litter, forest residue, corn stover, and winter wheat straw. In the following sections of this chapter the Jackson Purchase Region will be further described (4.1) followed by a detailed discussion of the annual and monthly availability of each feedstock (4.2). Finally, the selection of the biomass, plant, and market distributions will be discussed (4.3).

4.1 Jackson Purchase Region of Kentucky

As outlined in red in Fig. 4-1 below, the Jackson Purchase Region in Western Kentucky consists of Ballard, Calloway, Carlisle, Fulton, Graves, Hickman, Marshall, and McCracken counties with a population of approximately 200,000 (U.S. Census Bureau, 2010).

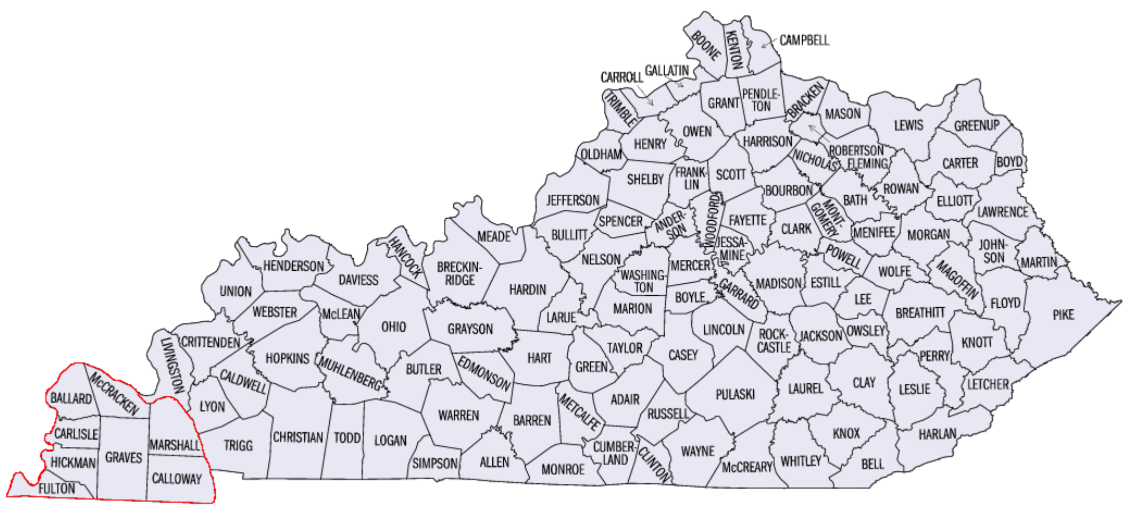


Figure 4-1: Jackson Purchase Region in Western Kentucky

Along with being bordered by the Mississippi, Ohio and Tennessee Rivers which are potential transportation modes, the Jackson Purchase Region also has an abundance of non-food biomass resources such as agricultural residues from soybean, corn, and wheat farming, poultry litter, and forest residues. A robust chemical industry is also present in the region, providing potential markets for chemical products created. Due to the wide variety of biomass resources, transportation options, and potential product markets, the Jackson Purchase Region in Western Kentucky makes an ideal case study for validating the framework.

4.2 Biomass Feedstocks

After analyzing the Jackson Purchase Region, the feedstocks to be used in the case study were identified as poultry litter, forest residue, corn stover, and winter wheat straw for the production of fuels and chemicals. These feedstocks were chosen based on availability in the Jackson Purchase Region, competition with food resources, and/or as they are currently seen as a waste stream that if not utilized in a proper way has potential for detrimental environmental and animal health effects. It should be noted coal is prevalent in this area as the Jackson Purchase Region is the northern section of the Gulf Province Coal Region of the United States (Tully,1996) but is not currently mined (EIA, 2010). Even though coal can be co-fired with multiple biomass feedstocks (Baliban et al, 2011), it is not considered as a potential feedstock due to not being readily available.

Poultry litter is the bedding and waste materials removed from poultry houses (Jensen et al, 2010). This biomass feedstock range not only consists of manure but also the initial bedding material as well as any feathers from the poultry itself, excess feed and supplements not digested by the poultry. There are currently many applications for the use of poultry litter. One of those applications commonly being used is as an inexpensive fertilizer to meet the nitrogen needs. However, excess phosphorous in the poultry litter can potentially cause eutrophication of the water supply which may lead to hypoxia, the depletion of oxygen in the water (Howry et al, 2008), thus, potentially killing any species dependent on oxygen in the water supply such as fish and amphibians. If properly treated, poultry litter can also be used to feed cattle (FDA, 2008). However, negative impacts can be seen by doing this, such as, the spread of Bovine Spongiform Encephalopathy (Mad Cow Disease) which is thought to be linked to Creutzfeldt-Jakob Disease, a fatal human neurological disease (Takemura, 2004). Before taken out of the poultry house, ammonia is often emitted from poultry litter at relative high rates causing poor poultry performance by compromising the immune system and damaging the respiratory system of the poultry (Carlisle, 1984). Poultry litter has been chosen for this case study due to not only potentially having positive environmental and health impacts as it is not used for the current applications described above but also its great potential for the production of fuels and chemicals (Perara et al, 2010).

Forest residue refers to the treetops, branches, stumps, dead-wood, small-diameter wood, and undergrowth unsuitable for saw logs. The removal of forest residue is seen as a fire risk prevention practice as it reduces the risks and losses from catastrophic fires as well as improves forest health (US DOE, 2011). However, the removal of forest residues may have detrimental ecosystem and nutritional effects after the clear-cutting of a forest (Hacker, 2005). Therefore, only forest residues from sustainable forestry practices are to be considered as potential biomass feedstock for the case study.

Crop residues for bioenergy applications are seen as desirable feedstocks because of their immediate availability, low cost, and relatively concentration in the major grain growing regions where equipment and labor are currently located (US DOE, 2011). For these reasons, two crop residues have been chosen for the case study: (1) corn stover and (2) winter wheat straw. Corn stover consists of the stalk, leaf, cob, and husk left in the field after the harvest of the respective corn grain, while winter wheat straw comprises of the straw and stubble. The harvest for corn and winter wheat grains occurs from August to November and June to August, respectively. The following sections will discuss in detail the annual availability (4.2.1), harvest progress (4.2.2.) and monthly availability (4.2.3) for each of the biomass feedstocks selected for the Jackson Purchase Region case study.

4.2.1 Annual Availability

Information regarding the availability of each biomass feedstock is readily recorded (on national, state, and county levels) and provided to the general public though a multitude of various sources. Many of the sources provide the biomass availability in quantities of dry matter (moisture content not included). Since the biomass not only includes dry matter but water as well, the moisture content of the biomass feedstock must be included in the total biomass availability figure so the scenarios can be realistically modeled. Through Eqn. 4-1 below, given any information on a dry basis, the availability on a wet-basis for each biomass feedstock has been calculated.

$$Availability\ (wet\ basis) = \frac{Availability\ (dry\ basis)}{(1 - Moisture\ Content)} \tag{4.1}$$

All biomass feedstock information is also not given on a mass basis; therefore additional information was needed to determine the availability on a dry-basis before determining the availability on a wet-basis. The additional information along with the moisture content of each biomass feedstock is summarized in Table 4-1 below.

Table 4-1: Feedstock characteristics

Parameters	Values	Source
Poultry Litter		
moisture content	20%	Mitchell & Donald, 1995
manure rate	0.04 kg dry matter/head-day	Stanford, 1976
Forest Residue		
moisture content	49%	Miles et al, 1995
volumetric bulk density	25.6 lbs/ft^3	Brown, 2003
Corn Stover		
moisture content	15.5%	Millbrandt, 2005
residue: grain mass ratio	1 : 1	Millbrandt, 2005
grain bulk density	56 lbs/bushel	Millbrandt, 2005
Winter Wheat Straw		
moisture content	13.5%	Millbrandt, 2005
residue: grain mass ratio	1.3 : 1	Millbrandt, 2005
grain bulk density	60 lbs/bushel	Millbrandt, 2005

For poultry litter, the information provided by the USDA (2007) only included the end-of-year inventory (head count) for broilers, farms raised solely for the production of meat, and layers, farms raised solely for the production of eggs, in each county. The information provided, which is only gathered every 5 years, did not specify the type of poultry in the broilers and layers; therefore the manure rate for all poultry is assumed to be constant. From the head count, manure rate, and the moisture content, the poultry manure was calculated. As mentioned earlier, poultry litter comprises of not only manure but other biomass as well. It has been assumed the amount calculated includes all biomass deemed as poultry litter. The amount of poultry litter available is further summarized for each county in Table 4-2 below. Although McCracken County (Paducah) is shown as not having any poultry farms, there are a few farms located in the county but information does not seem to have been disclosed regarding end-of-year inventory. For our purposes, McCracken County will not have any poultry litter available.

Table 4-2: Jackson Purchase Region Poultry Litter availability by county in tons (USDA, 2007)

Year	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
2007	19,550	25,549	18,236	14,502	176,121	116,112	16,467	---

Forest residue from federal land does not qualify as a renewable biomass feedstock under the federal Renewable Fuel Standard (RFS2) program (US EPA, 2007). For this reason, only residues from other sources will be considered. Since only logging residues have been recorded on a bi-annual basis in the Jackson Purchase Region by the Southern Research Station via the Timber Product Output Report given on a volumetric basis (TPO, 2009), it has been assumed these figures include all forest residue in the area and as being reported on a wet-basis. Given an assumed residue bulk density of 25.6 lbs/ft^3 for both softwood and hardwood, the annual availability for each county on a bi-annual basis from 2001 to 2009 has been calculated and further summarized in Table 4-3 below.

Table 4-3: Jackson Purchase Region Forest Residue availability by county in tons (TPO, 2009)

Year	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
2001	3,098	6,528	9,779	3,379	10,701	2,522	8,102	4,736
2003	9,203	10,176	11,558	3,904	14,976	2,790	8,896	1,600
2005	8,589	7,757	16,448	3,571	14,618	6,874	6,733	3,123
2007	13,146	8,755	14,976	1,830	9,766	4,915	7,987	2,010
2009	17,318	7,283	24,230	2,624	10,803	3,277	9,178	1,997

Crop residue information is the most readily accessible information due to the extensive record keeping of their respective food source whether that is for grains, beans, or sugar. The annual availability for corn stover (USDA, 2010a) and winter wheat straw (USDA, 2011a) were calculated by using the volume (bushels), the bulk density (lb/bushel), and the residue to grain ratio (lb/lb). The corn stover and winter wheat straw data has been reported based on the same moisture content as provided in Table 4-1. The annual availability in each county for corn stover from 2000-2010 and winter wheat straw from 2000 to 2011 is reflected in Table 4-4 and Table 4-5, respectively.

Table 4-4: Jackson Purchase Region Corn Stover availability by county in tons (USDA, 2010a)

Year	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
2000	103,578	108,156	91,238	134,873	204,439	150,416	34,776	47,040
2001	100,176	147,507	84,694	133,213	225,042	160,160	33,592	57,607
2002	63,706	108,332	69,608	83,076	186,760	119,028	26,754	26,275
2003	91,392	117,914	89,620	97,574	217,879	142,968	24,360	39,312
2004	104,698	130,382	96,158	121,985	240,178	187,314	34,776	62,546
2005	108,402	133,325	90,392	107,923	247,660	169,579	34,793	54,877
2006	102,214	126,039	93,139	86,716	211,218	162,579	23,229	47,376
2007	141,400	95,312	104,832	124,320	247,912	195,720	39,480	71,876
2008	116,200	85,400	93,212	78,316	218,260	157,640	21,420	47,180
2009	121,940	128,576	102,284	95,284	243,012	184,604	31,024	46,368
2010	95,452	80,892	90,888	89,824	221,844	163,632	23,548	42,028

Table 4-5: Jackson Purchase Region Winter Wheat Straw availability by county in tons (USDA, 2011a)

Year	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
2000	24,804	49,686	9,165	28,841	51,480	35,802	9,653	11,762
2001	26,239	54,464	9,329	37,690	50,310	34,320	8,424	12,847
2002	17,901	39,468	5,265	24,898	35,736	24,960	5,039	6,396
2003	20,475	46,644	9,945	30,830	44,870	41,106	2,535	6,638
2004	26,653	42,159	10,940	30,225	48,263	35,100	7,792	7,371
2005	23,696	31,941	7,488	26,130	32,175	29,718	4,352	4,298
2006	25,081	14,750	9,126	28,642	31,941	31,590	5,994	6,560
2007	13,163	12,636	9,165	27,203	21,216	29,000	4,611	5,046
2008	33,345	53,567	25,350	44,928	60,840	50,369	12,815	13,022
2009	21,450	28,275	12,168	25,740	27,885	26,052	7,995	9,165
2010	12,675	13,416	6,747	13,923	21,060	16,614	6,150	5,070
2011	33,072	47,190	17,550	27,885	70,902	39,195	18,174	13,416

4.2.2 Harvest Progress

The harvest progress as a percentage of completion is regularly recorded on a weekly basis throughout the year for corn (USDA, 2010b) and winter wheat grain (USDA, 2011b). Therefore, it has been assumed the new supply of corn stover and winter wheat straw follows along the same path as their respective grain. Forest residue and poultry litter have been assumed to have a constant throughout supply the year due to the removal of residue and litter for fire prevention mitigation purposes and health needs at the broilers and layers, respectively. Therefore, a constant new supply will be available each month for forest residue and poultry litter, whereas, the new supply of corn stover and winter wheat straw will solely depend on the harvest progress for their respective grains.

The information regarding the corn harvest completion percentage is available on a weekly basis (USDA, 2010b), as data is collected at the end of the week during the harvest months. Table 4-6 below shows the completion percentage for the harvest of corn grain at the end of the month starting in August and ending in November for the state of Kentucky from 2000 to 2010. It has been assumed these numbers are consistent throughout the state, therefore will be used for the Jackson Purchase Region case study.

Table 4-6: Kentucky corn grain harvest completion percentage (USDA, 2010b)

Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Aug	-	-	-	-	-	-	-	-	-	-	-
Sep	50	68	63	52	56	48	39	82	38	18	80
Oct	94	95	93	89	95	99	90	98	93	67	100
Nov	100	100	100	100	100	100	100	100	100	99	100
Dec	100	100	100	100	100	100	100	100	100	100	100

According to the information, data collection for corn grain harvest completion does not begin before September. However, when analyzing the data it was noticed a fair percentage, 15% or greater, had been completed in the first week of September, which was relatively high when compared to other weeks of September. For this reason it has been assumed 5% is completed in August (subtracted from September total). The monthly percent of new supply as a percentage of total production is shown in Table 4-7 below for the state of Kentucky.

Table 4-7: Kentucky corn grain new supply percentage of total production (USDA, 2010b)

Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Aug	5	5	5	5	5	5	5	5	5	5	5
Sep	45	63	58	47	51	43	34	77	33	13	75
Oct	44	27	30	37	39	51	51	16	55	49	20
Nov	6	5	7	11	5	1	10	2	7	33	-
Dec	-	-	-	-	-	-	-	-	-	-	-

As opposed to corn, winter wheat is planted in during the winter months (hence the name) and harvested from June to August. The harvest progress of winter wheat is not recorded for the state of Kentucky even though it is produced in the state. Therefore, the information related to Illinois winter wheat harvest will be used for the case study. The information is assumed to be consistent with state of Kentucky and the Jackson Purchase Region as it borders both regions. The harvest completion percentage for the years of 2000-2011 of winter wheat in Illinois (USDA, 2011b) can be seen in Table 4-8 below.

Table 4-8: Illinois winter wheat straw harvest completion percentage (USDA, 2011b)

Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Jun	35	53	79	58	76	71	65	78	37	46	64	43
Jul	100	100	100	98	100	100	100	100	100	94	100	100
Aug	100	100	100	100	100	100	100	100	100	100	100	100

With the information provided in Table 4-7 above, it was seen that winter wheat harvest completed in August for 2 of the 12 years, whereas, harvest was completed in July for the other years. To capture this observation, it has been assumed 1% (subtracting from the production in July) of total production is newly supplied in August. Table 4-9 below shows the winter wheat straw new supply percentage of total production.

Table 4-9: Illinois winter wheat straw new supply percentage of total production (USDA, 2011b)

Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Jun	35	53	79	58	76	71	65	78	37	46	64	43
Jul	64	46	20	41	23	28	34	21	62	53	35	56
Aug	1	1	1	1	1	1	1	1	1	1	1	1

Based on the monthly percent harvested for corn grain and winter wheat in Table 4-7 and Table 4-9, respectively, it is assumed that the respective crop residues will be harvested in the same month. Therefore, by using the average monthly Kentucky corn and Illinois winter wheat harvest progress, the Jackson Purchase Region's monthly harvest progress has been produced as shown in Table 4-10 below.

Table 4-10: Summary of estimated monthly corn stover and winter wheat straw new supply percentage of total production Jackson Purchase Region

Month	Corn Stover	Winter Wheat Straw
Jun	-	60%
Jul	-	39%
Aug	5%	1%
Sep	49%	-
Oct	38%	-
Nov	8%	-
Dec	-	-
Jan	-	-
Feb	-	-
Mar	-	-
Apr	-	-
May	-	-

4.2.3 Monthly Availability

To properly optimize the biorefinery supply chain based on biomass variability, the monthly availability of new supply must be determined. For that reason, the monthly availability of new supply it was calculated for each of the four biomass feedstocks. Poultry litter and forest residue have been assumed to be constant throughout the year, therefore, the monthly availability of these biomass feedstocks have been based on the number of days in that particular month. For instance, January has 31 days; therefore 8.49% (31/365) of total production is newly supplied during the month of January. The monthly new supply of corn stover and winter wheat straw was based on the annual production for that given county as well as the percentage of total production as outlined in Table 4-10 above. Poultry litter and forest residue will have a new supply of biomass each month throughout the year, whereas, corn stover and winter wheat straw will only have a new supply of biomass from August to November and June to August, respectively. Using the approach described, the monthly supply of poultry litter, forest residue, corn stover, and winter wheat straw for each county in Jackson Purchase Region is estimated as shown in Table 4-11, Table 4-12, Table 4-13 and Table 4-14, respectively. It should be noted that the monthly new supply of biomass is shown for June through May due to the harvest of winter wheat straw beginning in June.

Table 4-11: Monthly new supply of poultry litter by county (tons/month)

Month	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Jun	1,607	2,100	1,499	1,192	14,476	9,543	1,353	-
Jul	1,660	2,170	1,549	1,232	14,958	9,862	1,399	-
Aug	1,660	2,170	1,549	1,232	14,958	9,862	1,399	-
Sep	1,607	2,100	1,499	1,192	14,476	9,543	1,353	-
Oct	1,660	2,170	1,549	1,232	14,958	9,862	1,399	-
Nov	1,607	2,100	1,499	1,192	14,476	9,543	1,353	-
Dec	1,660	2,170	1,549	1,232	14,958	9,862	1,399	-
Jan	1,660	2,170	1,549	1,232	14,958	9,862	1,399	-
Feb	1,500	1,960	1,399	1,112	13,511	8,907	1,263	-
Mar	1,660	2,170	1,549	1,232	14,958	9,862	1,399	-
Apr	1,607	2,100	1,499	1,192	14,476	9,543	1,353	-
May	1,660	2,170	1,549	1,232	14,958	9,862	1,399	-

Table 4-12: Monthly new supply of forest residue by county (tons/month)

Month	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Jun	1,423	599	1,992	216	888	269	754	164
Jul	1,471	619	2,058	223	918	278	779	170
Aug	1,471	619	2,058	223	918	278	779	170
Sep	1,423	599	1,992	216	888	269	754	164
Oct	1,471	619	2,058	223	918	278	779	170
Nov	1,423	599	1,992	216	888	269	754	164
Dec	1,471	619	2,058	223	918	278	779	170
Jan	1,471	619	2,058	223	918	278	779	170
Feb	1,329	559	1,859	201	829	251	704	153
Mar	1,471	619	2,058	223	918	278	779	170
Apr	1,423	599	1,992	216	888	269	754	164
May	1,471	619	2,058	223	918	278	779	170

Table 4-13: Monthly new supply of corn stover by county (tons/month)

Month	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Jun	-	-	-	-	-	-	-	-
Jul	-	-	-	-	-	-	-	-
Aug	4,773	4,045	4,544	4,491	11,092	8,182	1,177	2,101
Sep	46,771	39,637	44,535	44,014	108,704	80,180	11,539	20,594
Oct	36,272	30,739	34,537	34,133	84,301	62,180	8,948	15,971
Nov	955	809	909	898	2,218	1,636	235	420
Dec	-	-	-	-	-	-	-	-
Jan	-	-	-	-	-	-	-	-
Feb	-	-	-	-	-	-	-	-
Mar	-	-	-	-	-	-	-	-
Apr	-	-	-	-	-	-	-	-
May	-	-	-	-	-	-	-	-

Table 4-14: Monthly new supply of winter wheat straw by county (tons/month)

Month	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Jun	12,898	18,404	6,845	10,875	27,652	15,286	7,088	5,232
Jul	19,843	28,314	10,530	16,731	42,541	23,517	10,904	8,050
Aug	331	472	176	279	709	392	182	134
Sep	-	-	-	-	-	-	-	-
Oct	-	-	-	-	-	-	-	-
Nov	-	-	-	-	-	-	-	-
Dec	-	-	-	-	-	-	-	-
Jan	-	-	-	-	-	-	-	-
Feb	-	-	-	-	-	-	-	-
Mar	-	-	-	-	-	-	-	-
Apr	-	-	-	-	-	-	-	-
May	-	-	-	-	-	-	-	-

4.3 Products

The products to be created from poultry litter, forest residue, corn stover, and winter wheat straw are gasoline, diesel, residual fuel oil, natural gas, electricity, and ethanol. Gasoline, diesel, natural gas, electricity, and ethanol were selected based on being readily consumed by the general public as well as industry throughout the year in all demographic regions of the United States and Kentucky. Residual fuel oil is the remaining heavy fraction from oil refining used for various applications such as fuel for large ships, electricity generation, space heating, and other purposes (EIA, 2011). When compared to biomass feedstocks, information regarding the demand or creation of said products is available through an array of sources on a monthly basis for the state of Kentucky and the United States.

4.3.1 Kentucky Monthly Product Demand

As provided by the Energy Information Agency (EIA, 2012b) the monthly electricity generated in terra watt-hours for the state of Kentucky can be seen on a monthly basis in Table 4-15 below. The amount generated for the state has been assumed to be the amount consumed for the purposes of the case study. A ‘double-peak’ of electricity generation is seen for Kentucky during the winter and summer months due electricity consumption for heating and cooling buildings. This phenomenon is not common throughout the United States as natural gas is commonly used for heating purposes. Also, Kentucky has the 2nd lowest electricity rates in the country as roughly 90% of electricity generation comes from coal-fired power plants as (EIA, 2012b).

Table 4-15: Kentucky electricity generation (TWh/month)

Year	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
2001-02	9.2	7.9	7.6	6.7	8.0	8.2	7.2	8.2	7.4	7.7	8.0	8.8
2002-03	8.6	7.4	6.5	6.2	7.7	8.8	7.6	7.1	7.1	7.0	7.7	8.5
2003-04	8.6	7.1	6.8	7.0	8.4	9.1	8.1	7.7	6.8	7.9	8.0	8.5
2004-05	8.2	7.6	7.3	6.8	8.5	8.3	7.4	7.9	7.3	7.8	8.6	9.1
2005-06	9.0	8.6	7.5	7.4	9.0	8.8	8.1	7.8	6.9	7.9	8.3	9.3
2006-07	9.1	7.9	7.9	8.2	8.6	9.2	8.4	7.9	6.5	7.1	8.2	8.6
2007-08	9.9	8.0	7.7	7.4	8.2	9.4	8.3	8.2	7.1	7.0	7.9	8.9
2008-09	8.6	8.2	7.6	8.2	8.6	8.5	7.3	7.7	6.8	7.0	8.1	7.6
2009-10	8.4	7.2	7.0	6.6	8.3	9.2	8.5	7.8	6.7	7.0	8.8	9.0
2010-11	9.5	7.9	7.2	7.3	9.3	9.5	8.1	7.9	7.2	7.7	8.3	9.9

The natural gas delivered to consumers for the state of Kentucky is also recorded on a monthly basis (EIA, 2012d) as seen in Table 4-16 below. The numbers include natural gas consumption for industrial usage, heating of homes, and vehicle fuel. For our purposes, it is assumed the natural gas is consumed in the same as of delivery.

Table 4-16: Kentucky natural gas delivered (Billion cubic ft/month)

Year	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
2001-02	9.9	10.0	12.6	16.3	23.2	26.1	24.5	23.2	14.9	12.3	11.6	13.8
2002-03	10.9	11.1	14.6	21.1	27.6	34.8	29.0	20.6	14.0	10.8	9.3	9.5
2003-04	10.3	10.4	13.2	16.9	27.2	32.6	27.6	21.6	15.8	12.3	11.2	10.8
2004-05	11.4	10.9	13.4	17.7	27.2	29.4	24.0	24.6	15.6	13.6	13.7	12.7
2005-06	14.1	12.1	14.1	19.3	29.0	23.1	23.7	20.4	14.4	13.1	12.1	12.9
2006-07	13.8	11.1	14.9	18.0	22.9	26.9	29.9	20.0	17.4	12.6	11.4	10.3
2007-08	16.7	11.8	13.9	18.7	24.8	31.4	26.4	23.1	15.6	11.9	11.8	11.2
2008-09	11.2	10.3	12.1	18.1	24.6	30.6	22.5	18.1	13.1	9.3	9.2	9.7
2009-10	10.9	10.4	13.3	15.8	26.1	31.8	27.8	19.6	11.4	11.2	11.7	12.8
2010-11	13.7	11.5	11.5	17.0	32.0	32.0	23.4	20.6	13.7	13.3	11.9	12.7

In Table 4-17 below, the Kentucky monthly special fuel sales is shown (US DOT, 2011) to represent the gross volume of diesel and other alternative fuels reported by the state motor fuel tax agency. The volume of alternative fuels is assumed to be negligible; therefore, the monthly special fuel sales comprises of all diesel. Table 4-17 below represents the monthly amount of diesel sold in Kentucky from August 2004 to July 2011. Even though diesel as well as gasoline can be bought (or sold to customers) in one area and consumed in another (for example, buying gas in Kentucky and burning it while driving in Illinois), is assumed the amount sold reflects the demand for diesel and gasoline for the state of Kentucky as these instances cannot be accounted for in this case study.

Table 4-17: Kentucky special fuels sales (Million gallons/month)

Year	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
2004-05	68.9	75.7	68.7	66.0	73.2	63.3	67.2	79.7	73.7	63.7	80.5	69.4
2005-06	68.1	78.3	66.4	85.9	71.1	83.4	67.3	82.0	70.7	68.4	79.5	65.1
2006-07	79.8	76.0	73.9	71.9	70.8	68.4	70.3	81.2	69.6	70.9	77.3	71.6
2007-08	80.3	70.1	81.7	69.7	64.9	69.7	64.9	70.0	66.6	69.7	73.2	68.3
2008-09	70.0	73.1	75.0	61.0	60.6	60.8	56.2	63.9	56.5	61.4	62.7	58.2
2009-10	68.1	66.3	69.5	58.3	62.0	62.4	55.2	70.9	66.3	65.4	69.8	66.2
2010-11	66.6	68.3	71.4	61.0	62.5	62.6	59.6	69.6	63.6	65.8	67.0	62.3

Table 4-18 represents the gasoline sales for the state of Kentucky in millions of gallons per month from August 2004 to July 2011 (US DOT 2011).

Table 4-18: Kentucky gasoline sales (Million gallons/month)

Year	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
2004-05	200.1	188.0	164.3	180.4	241.8	224.9	166.7	175.8	186.9	200.2	194.6	198.2
2005-06	189.3	172.7	180.2	181.1	184.3	169.2	164.9	189.9	188.6	194.6	190.0	191.4
2006-07	199.3	180.5	188.5	185.3	186.4	177.6	166.3	190.9	185.7	199.7	188.0	198.5
2007-08	198.0	178.8	193.4	163.2	191.4	174.1	159.9	171.6	178.3	184.1	180.5	185.8
2008-09	186.3	172.6	186.5	178.6	185.8	171.4	167.7	185.0	188.1	191.2	191.4	194.1
2009-10	192.7	183.0	185.3	177.6	188.0	168.3	157.5	187.5	188.7	193.5	193.4	200.2
2010-11	198.1	185.1	186.9	180.6	181.6	164.2	160.5	182.5	178.5	187.3	187.6	189.5

Residual fuel oil data was sparsely available for the past years for the state of Kentucky. Therefore, residual fuel oil supplied for the United States (EIA, 2012d) Table 4-19 will be used as the basis determining the demand of residual fuel oil.

Table 4-19: United States Residual Fuel Oil Supplied (Millon gallons/month)

Year	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
2001-02	1,048	782	958	852	736	924	779	1,069	920	885	843	799
2002-03	797	788	846	990	1,083	1,003	1,044	1,202	980	876	873	1,012
2003-04	1,168	832	932	886	1,031	1,276	1,162	1,148	1,045	1,012	1,038	1,173
2004-05	1,013	988	1,117	1,085	1,195	1,315	1,088	1,000	1,008	954	1,045	1,176
2005-06	1,368	1,292	1,289	1,231	1,335	1,216	960	1,023	861	764	779	868
2006-07	1,000	678	797	662	953	988	1,112	941	859	898	924	871
2007-08	991	849	815	968	866	889	634	767	891	876	861	891
2008-09	665	655	777	656	980	990	527	769	853	564	713	415
2009-10	615	428	644	561	758	801	606	691	743	676	630	775
2010-11	620	646	637	696	684	811	737	712	756	622	593	411

4.3.2 Jackson Purchase Monthly Product Demand

The consumption or demand for Kentucky has been clearly recorded year-after-year on a monthly basis for gasoline, diesel, natural gas, electricity, and residual fuel oil. Assuming product consumption or demand is constant throughout the state and the United States, the demand on a per capita basis can be computed using the population data for the respective regions. From this, the monthly product demand for each county in the Jackson Purchase Region can be calculated based on its respective population. The process for creating the county demand for each of the products is shown below in Fig. 4-2.

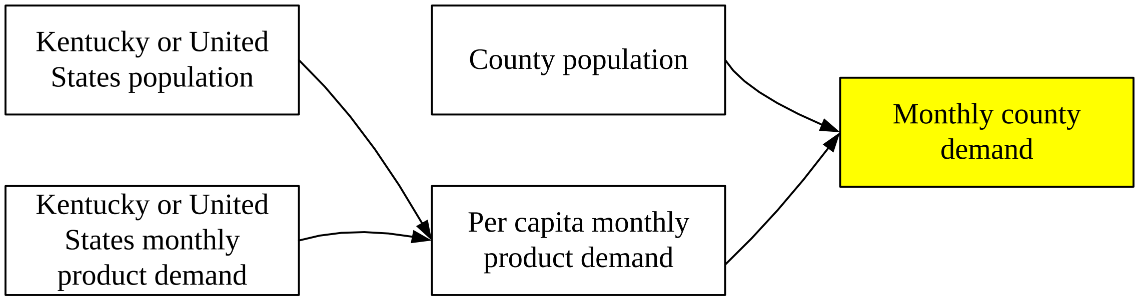


Figure 4-2: Methodology for county product demand

The population for the United States, the state of Kentucky, and the Jackson Purchase Region (US Census, 2010) for the years 2004-2010 is shown in Table 4-20 below. Over the past few years, the population in the Jackson Purchase Region has been stable accounting for approximately 4.5% of the total state population.

Table 4-20: United States, Kentucky, and Jackson Purchase population by year (2004-2010)

Location	2004	2005	2006	2007	2008	2009	2010
United States	293,045,739	295,753,151	298,593,212	301,579,895	304,374,846	307,006,550	309,349,689
Kentucky	4,147,970	4,182,293	4,219,374	4,256,278	4,287,931	4,314,113	4,339,367
Jackson Purchase	192,887	193,534	194,270	194,983	195,598	196,182	196,393

The county population in the Jackson Purchase Region for the past 40 years can be seen in Fig. 4-3 below along with Table 4-21 representing a snapshot of that time frame from 2004-2010. Even though the population has increased in the area along with the population in a portion of the counties, an abnormal population decrease or spike is not seen over this time frame. Since the population of the region is stable, it can be assumed the demand for various products is stable as well.

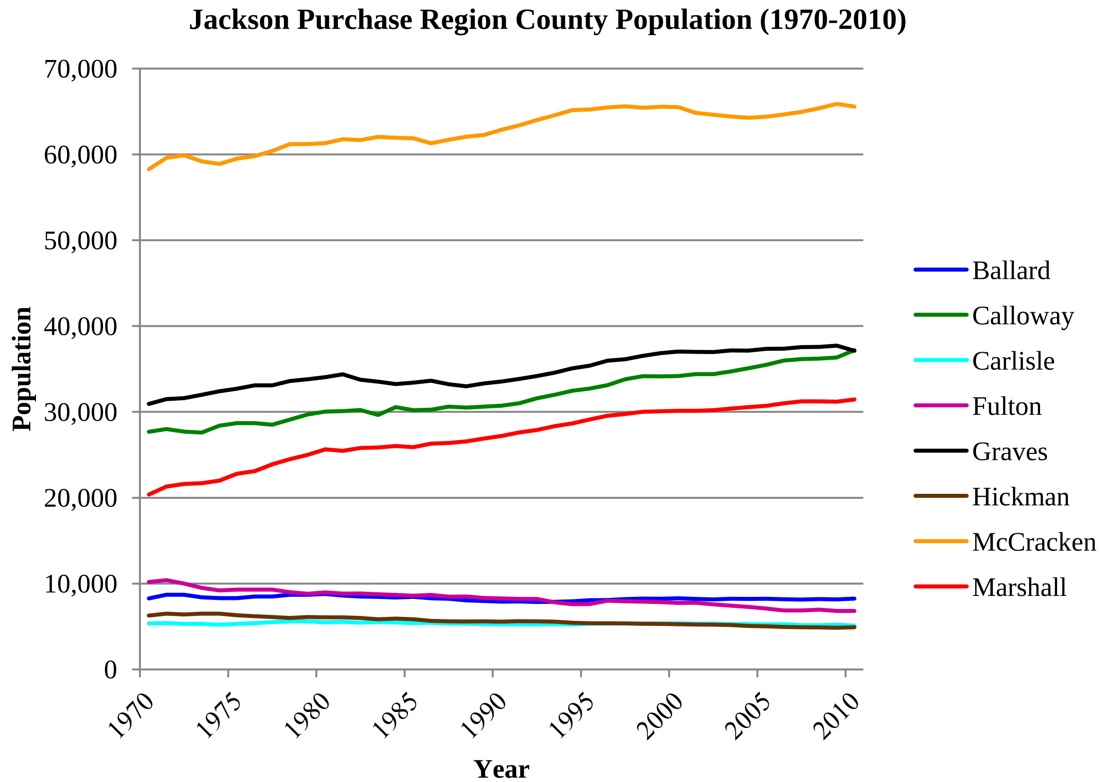


Figure 4-3: Population by county in the Jackson Purchase Region (1970-2010)

Table 4-21: Population by county in the Jackson Purchase Region (2004-2010)

County	2004	2005	2006	2007	2008	2009	2010
Ballard	8,217	8,238	8,169	8,138	8,200	8,161	8,249
Calloway	35,087	35,477	35,988	36,161	36,204	36,348	37,191
Carlisle	5,290	5,249	5,255	5,156	5,156	5,209	5,104
Fulton	7,276	7,089	6,867	6,862	6,958	6,814	6,813
Graves	37,144	37,353	37,373	37,562	37,573	37,719	37,121
Hickman	5,063	5,019	4,953	4,901	4,893	4,851	4,902
Marshall	30,550	30,705	31,007	31,239	31,226	31,200	31,448
McCracken	64,260	64,404	64,658	64,964	65,388	65,880	65,565

As pointed out in Fig. 4-1 above, using the population of Kentucky and the individual county population, the county monthly demand for each product can easily be calculated given the monthly demand for the state of Kentucky. The 2010-2011 gasoline sales data (US DOT, 2011) along with the 2010 population data was used to estimate the monthly demand for each county as shown in Table 4-22 below.

Table 4-22: County gasoline monthly demand (gallons/month)

Month	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Aug	363,613	1,592,991	231,850	310,005	1,663,224	219,769	1,376,012	2,882,906
Sep	358,215	1,569,293	228,413	305,429	1,638,529	216,499	1,355,538	2,840,264
Oct	342,382	1,501,133	218,228	291,596	1,566,674	206,807	1,296,394	2,715,783
Nov	355,210	1,555,862	226,492	302,857	1,624,531	214,683	1,343,895	2,815,943
Dec	380,257	1,679,187	240,885	320,671	1,737,192	228,532	1,443,805	3,020,944
Jan	315,990	1,395,253	200,188	266,513	1,443,606	189,916	1,199,812	2,510,417
Feb	346,496	1,531,762	219,515	291,916	1,583,959	208,137	1,316,759	2,754,894
Mar	340,913	1,507,758	215,930	287,096	1,558,660	204,751	1,295,863	2,710,834
Apr	369,236	1,632,608	233,868	311,016	1,687,934	221,771	1,403,227	2,935,682
May	360,416	1,593,334	228,291	303,644	1,647,488	216,505	1,369,606	2,865,216
Jun	376,390	1,664,110	238,393	317,061	1,720,532	226,075	1,430,297	2,992,361
Jul	373,984	1,653,611	236,843	315,026	1,709,579	224,622	1,421,255	2,973,312

As mentioned earlier, it is assumed that the monthly diesel demand for each county is based on the monthly special fuel sales. Utilizing the 2010-2011 (US DOT, 2011) Kentucky special fuel sales data and the state and county population, the monthly county demand was generated as shown in Table 4-23below.

Table 4-23: County diesel monthly demand (gallons/month)

Month	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Aug	135,692	594,819	86,509	115,600	620,838	81,997	513,751	1,076,048
Sep	146,487	641,370	93,402	124,955	669,803	88,567	554,071	1,160,812
Oct	135,647	594,739	86,455	115,560	620,709	81,945	513,675	1,075,944
Nov	137,665	602,528	87,781	117,425	629,361	83,263	520,540	1,090,392
Dec	129,979	574,254	82,360	109,570	594,018	78,119	493,792	1,032,894
Jan	118,698	524,689	75,224	100,008	542,661	71,322	451,130	943,558
Feb	134,346	593,539	85,139	113,264	614,038	80,748	510,462	1,067,701
Mar	138,776	613,214	87,930	116,967	634,236	83,413	527,258	1,102,727
Apr	133,581	590,223	84,611	112,598	610,425	80,280	507,441	1,061,339
May	123,751	547,187	78,374	104,257	565,766	74,331	470,386	983,895
Jun	146,646	647,887	92,908	123,621	670,151	88,140	557,086	1,165,182
Jul	127,703	564,467	80,866	107,622	583,688	76,722	485,266	1,014,985

For our purposes, it was assumed that the monthly natural gas delivered is consumed in the same month. With this in mind, the county natural gas demand has been populated in Table 4-24 below using the 2010-2011 natural gas delivered figures along with respective county and state population.

Table 4-24: County natural gas monthly demand (thousand cubic ft/month)

Month	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Aug	363,613	1,592,991	231,850	310,005	1,663,224	219,769	1,376,012	2,882,906
Sep	358,215	1,569,293	228,413	305,429	1,638,529	216,499	1,355,538	2,840,264
Oct	342,382	1,501,133	218,228	291,596	1,566,674	206,807	1,296,394	2,715,783
Nov	355,210	1,555,862	226,492	302,857	1,624,531	214,683	1,343,895	2,815,943
Dec	380,257	1,679,187	240,885	320,671	1,737,192	228,532	1,443,805	3,020,944
Jan	315,990	1,395,253	200,188	266,513	1,443,606	189,916	1,199,812	2,510,417
Feb	346,496	1,531,762	219,515	291,916	1,583,959	208,137	1,316,759	2,754,894
Mar	340,913	1,507,758	215,930	287,096	1,558,660	204,751	1,295,863	2,710,834
Apr	369,236	1,632,608	233,868	311,016	1,687,934	221,771	1,403,227	2,935,682
May	360,416	1,593,334	228,291	303,644	1,647,488	216,505	1,369,606	2,865,216
Jun	376,390	1,664,110	238,393	317,061	1,720,532	226,075	1,430,297	2,992,361
Jul	373,984	1,653,611	236,843	315,026	1,709,579	224,622	1,421,255	2,973,312

The amount of electricity generated in the state of Kentucky was assumed to be the total amount consumed, not considering loss due to grid inefficiencies. As with prior products, the county monthly electricity demand was generated, as shown in Table 4-25 below, using the 2010 state and county population data along with the 2010-2011 (EIA, 2012) electricity generation numbers.

Table 4-25: County electricity monthly demand (MWh/month)

Month	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Aug	16,615	72,825	10,591	14,156	76,018	10,040	62,900	131,752
Sep	15,793	69,180	10,067	13,465	72,231	9,545	59,758	125,188
Oct	14,032	61,480	8,946	11,960	64,184	8,480	53,105	111,244
Nov	14,850	65,081	9,465	12,653	67,929	8,972	56,210	117,739
Dec	16,499	72,943	10,453	13,899	75,427	9,911	62,703	131,178
Jan	15,531	68,693	9,832	13,081	71,009	9,325	59,040	123,501
Feb	17,006	75,224	10,766	14,321	77,751	10,212	64,647	135,214
Mar	14,664	64,828	9,287	12,354	67,032	8,807	55,726	116,580
Apr	13,674	60,433	8,661	11,523	62,498	8,214	51,951	108,695
May	13,597	60,084	8,615	11,458	62,142	8,170	51,655	108,062
Jun	16,533	73,100	10,469	13,926	75,570	9,930	62,823	131,426
Jul	16,805	74,281	10,643	14,160	76,806	10,097	63,850	133,551

Ethanol is currently used as a fuel additive for performance and emissions reduction purposes as well as consumed as a typical liquid transportation fuel (i.e. E85). Therefore, the monthly county demand as shown in Table 4-26, has been computed based on 10% of the gasoline demand described earlier.

Table 4-26: County ethanol monthly demand (gallons/month)

Month	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Aug	36,361	159,299	23,185	31,000	166,322	21,977	137,601	288,291
Sep	35,821	156,929	22,841	30,543	163,853	21,650	135,554	284,026
Oct	34,238	150,113	21,823	29,160	156,667	20,681	129,639	271,578
Nov	35,521	155,586	22,649	30,286	162,453	21,468	134,390	281,594
Dec	38,026	167,919	24,089	32,067	173,719	22,853	144,380	302,094
Jan	31,599	139,525	20,019	26,651	144,361	18,992	119,981	251,042
Feb	34,650	153,176	21,952	29,192	158,396	20,814	131,676	275,489
Mar	34,091	150,776	21,593	28,710	155,866	20,475	129,586	271,083
Apr	36,924	163,261	23,387	31,102	168,793	22,177	140,323	293,568
May	36,042	159,333	22,829	30,364	164,749	21,651	136,961	286,522
Jun	37,639	166,411	23,839	31,706	172,053	22,608	143,030	299,236
Jul	37,398	165,361	23,684	31,503	170,958	22,462	142,126	297,331

Residual fuel oil supply is assumed to be constant throughout the country; therefore, using the population of the United States the per capita monthly demand was calculated. Furthermore, the demand for each individual county was calculated using the per capita monthly demand and the population of the respective county as seen in Table 4-27 below.

Table 4-27: County residual fuel oil monthly demand (gallons/month)

Month	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Aug	16,526	74,509	10,225	13,649	74,368	9,821	63,003	131,353
Sep	17,236	77,710	10,665	14,236	77,564	10,243	65,710	136,997
Oct	16,977	76,543	10,505	14,022	76,399	10,089	64,724	134,940
Nov	18,546	83,618	11,475	15,318	83,460	11,021	70,705	147,412
Dec	18,227	82,179	11,278	15,054	82,024	10,832	69,489	144,875
Jan	21,630	97,519	13,383	17,864	97,335	12,854	82,460	171,918
Feb	19,662	88,647	12,166	16,239	88,480	11,684	74,958	156,278
Mar	18,991	85,622	11,751	15,685	85,461	11,286	72,401	150,946
Apr	20,159	90,889	12,473	16,650	90,718	11,980	76,854	160,230
May	16,596	74,822	10,268	13,707	74,681	9,862	63,268	131,905
Jun	15,825	71,348	9,792	13,070	71,213	9,404	60,330	125,781
Jul	10,971	49,464	6,788	9,061	49,371	6,520	41,826	87,201

4.4 Biomass, Biorefinery, and Market Distribution Locations

According to the framework provided in Chapter 3, the next step is to select the biomass, biorefinery, and market distribution locations. The location of each biomass is different due to the source being different, with the exception of corn stover and winter wheat straw (corn stover and winter wheat straw from fields, poultry litter from broilers and layers, forest residue from forests or woody areas). The number of biomass feedstock locations in each county was determined using the highest recent annual total Jackson Purchase Region production and the respective county production for that year (provided in prior tables) as well as the maximum annual capacity (determined as described in the following paragraph) to be held at each biomass location. Note that corn stover and winter wheat straw locations are deemed to be the same as a new supply of biomass is only available for a portion of the year coming from nearby fields.

The determination of the maximum annual capacity for each biomass feedstock was based on estimated as described below in further detail. Broilers and layers cover the Jackson Purchase Region in great number and typically are clustered. Therefore 20,000 tons was has been determined as the maximum available annual capacity for poultry litter to account for this observation as well as to keep the number of total poultry locations at a reasonable level for modeling. When compared to poultry litter and corn stover capacities in Table 4-29 below, forest residue has a relatively low maximum annual capacity of 5,000 tons as sustainable practices are assumed which results in lower availability. Since corn stover and winter wheat straw are only collected during a few months of the year and corn stover being the largest biomass resource in the area, the annual maximum capacity of 37,500 tons of corn stover was used to determine the number of locations for corn stover and winter wheat straw. Table 4-28 below summarizes the maximum annual capacity for each biomass location as well as the data year used to determine the number of locations in each county.

Table 4-28: Biomass feedstock location information

Feedstock	Maximum Capacity (Wet Tons)	Data Year Used	Total Locations
Chicken Litter	20,000	2007	19
Forest Residue	5,000	2009	24
Corn Stover	37,500	2007	31
Winter Wheat Straw	37,500	2007	31

The maximum capacity per location from Table 4-28 and the county supply data were used to determine the number of biomass feedstock locations for each county as summarized in Table 4-29 below. If partial locations were calculated, the numbers were then rounded-up for all counties and biomass types. The total number of poultry litter, forest residue, corn stover and winter wheat straw locations are 19, 24, and 31, respectively.

Table 4-29: Number of county biomass locations

Feedstock	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Chicken Litter	1	2	1	1	9	6	1	0
Forest Residue	4	2	5	1	3	1	2	1
Corn Stover & Winter Wheat Straw	4	3	3	4	7	6	2	2

Table 4-30 below summarizes the seat of each county in the Jackson Purchase Region, which will be used for the potential biorefinery locations to keep at a reasonable level.

Table 4-30: Jackson Purchase Region county seats

County	*Seat*
Ballard	*Wickliffe*
Calloway	*Murray*
Carlisle	*Bardwell*
Fulton	*Hickman*
Graves	*Mayfield*
Hickman	*Clinton*
Marshall	*Benton*
McCracken	*Paducah*

Figure 4-3 below shows the location of each county seat (shown as red tabs) with the counties outlined in various colors per Google Maps.

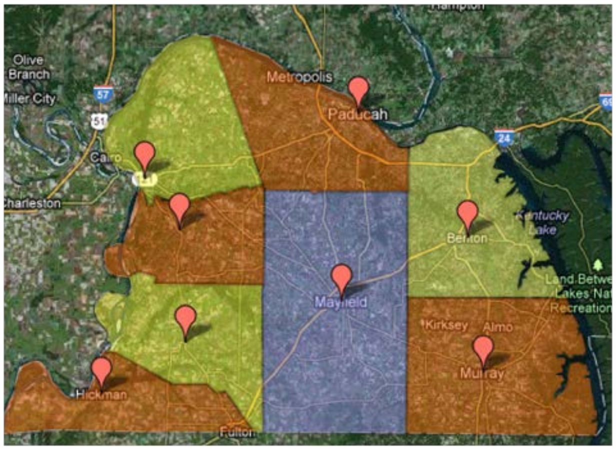


Figure 4-4: Plant locations

Prior work has been completed via geographic information systems (GIS) to identify the location of poultry houses in the Jackson Purchase Region (Zhang). These locations were then inserted into a Google Map as seen in Fig. 4-4 (as blue tabs) with the Jackson Purchase Region outlined in red.

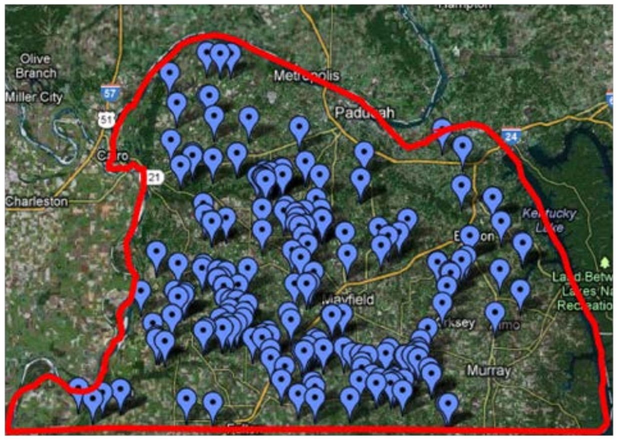


Figure 4-5: Location of all the broilers and layers

Given the number of poultry litter locations per county from Table 4-30, the highest density poultry litter locations from Fig. 4-5 were identified as the supply locations for poultry litter in this study. Figure 4-6 shows each poultry litter location as blue tabs chosen with the counties once again outlined in a Google Map. Note that broilers and layers were identified in McCracken County (Paducah) but none were selected based on the lack of information of poultry inventory data due to disclosure purposes.

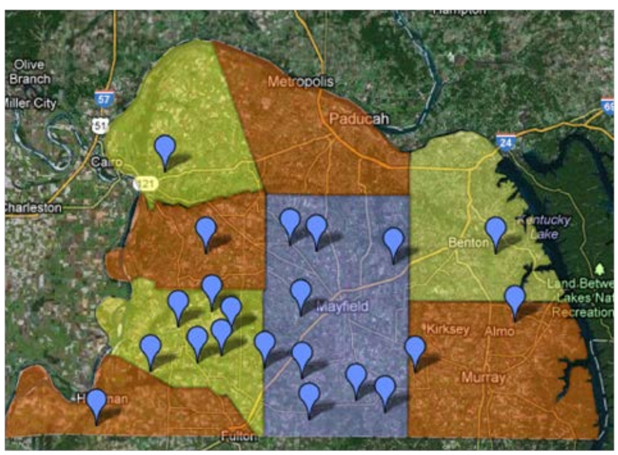


Figure 4-6: Poultry litter locations

From the poultry litter and plant locations highlighted in Fig. 4-5 and Fig. 4-6, respectively, the directions feature in Google Maps was used to find the distances between all potential plant locations and the poultry litter locations as summarized in Table 4-31 below. It is assumed that all routes selected via Google Maps are suitable to transport the biomass to the plant locations.

Table 4-31: Distance from poultry litter locations to plant locations (miles)

County	Location	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Ballard	1	3.2	58.1	11.8	44.1	34.2	26.6	51.5	30.5
Calloway	2	46.0	10.2	41.4	45.7	15.3	35.5	24.0	42.8
	3	61.6	10.1	57.0	61.2	26.8	55.6	15.1	43.3
Carlisle	4	13.4	47.0	4.8	34.4	23.1	17.0	40.4	35.5
Fulton	5	47.4	55.9	38.8	5.8	43.4	23.9	62.4	72.5
Graves	6	21.1	35.0	16.6	49.5	11.1	24.9	28.5	23.7
	7	25.6	33.0	21.0	48.8	9.1	31.4	25.7	21.8
	8	39.8	26.6	35.2	52.0	9.1	34.6	15.5	24.1
	9	29.6	29.7	23.5	37.0	6.1	19.8	25.2	35.2
	10	36.6	34.2	28.0	26.6	14.5	13.2	33.6	43.6
	11	42.2	27.0	36.8	28.4	13.3	21.9	32.3	42.3
	12	46.2	25.2	37.7	28.8	18.5	22.8	39.1	49.0
	13	51.8	18.0	43.3	34.3	15.9	28.4	33.3	43.3
	14	48.6	16.3	48.2	39.3	18.0	33.3	35.4	45.4
Hickman	15	26.2	41.0	17.6	18.7	25.8	2.7	44.9	51.9
	16	28.2	40.6	19.6	22.2	18.6	4.7	37.6	47.7
	17	31.1	49.8	22.6	12.4	31.0	7.7	50.1	56.8
	18	28.3	42.2	19.8	23.9	20.2	6.4	39.2	41.1
	19	22.1	47.1	13.5	26.2	23.2	8.7	44.1	47.8
	20	21.9	47.3	13.4	21.0	26.9	3.6	46.0	47.6
Marshall	21	54.4	19.4	49.8	65.8	25.3	48.4	5.4	32.7

Based on the number of available forest residue locations provided in Table 4-29, the relevant region in each county were identified by zooming into each county in Google Maps and finding the dense, dark green areas as well as attempting to evenly distribute the locations within each county. These areas were assumed to represent canopy, thus, forest or woody areas. The forest residue locations (green tabs) used in the case study can be seen in Fig. 4-7 below.

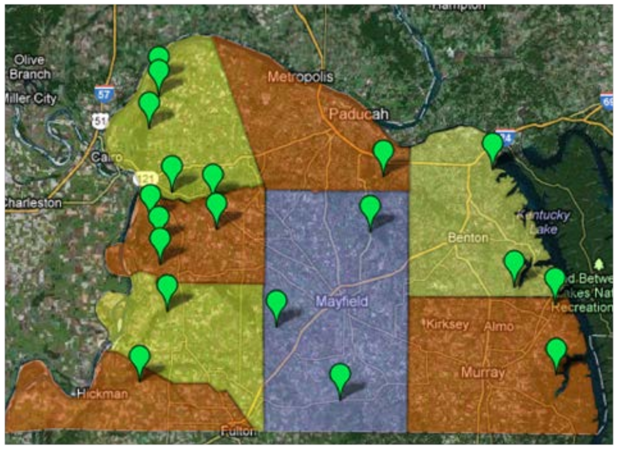


Figure 4-7: Forest residue locations

The directions feature in Google Maps was again utilized to find the distances from the forest residue locations to potential plant locations, which is summarized in Table 4-32 below.

Table 4-32: Distance from forest residue locations to biorefinery locations (miles)

County	Location	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Ballard	1	16.1	73.5	24.6	56.9	47.8	39.5	54.8	29.3
	2	12.2	74.0	20.7	53.1	43.1	35.6	55.3	29.8
	3	8.5	72.6	17.1	49.4	39.5	31.9	53.9	28.4
	4	3.9	51.2	13.6	45.9	27.3	28.4	44.6	32.2
Calloway	5	67.9	15.0	63.4	66.2	33.5	54.6	19.0	43.1
	6	62.5	10.0	57.9	61.2	31.8	55.2	26.0	54.3
Carlisle	7	9.6	45.5	7.9	40.2	21.6	22.7	38.9	29.2
	8	16.2	55.4	7.6	29.2	26.6	11.7	45.7	41.9
	9	7.9	55.9	6.1	38.5	32.0	21.0	49.3	39.6
	10	14.8	44.2	8.8	38.4	20.3	20.9	37.6	31.5
	11	11.9	53.9	3.4	32.8	30.0	18.3	47.3	37.6
Fulton	12	34.1	48.1	25.6	6.8	37.9	10.7	57.0	59.8
Graves	13	39.5	31.1	34.9	51.0	10.5	33.5	16.0	18.8
	14	37.8	31.4	29.3	32.4	13.4	14.4	32.5	42.5
	15	49.2	19.5	40.7	31.8	13.2	25.8	33.7	43.8
Hickman	16	23.6	48.6	15.0	21.1	28.2	5.3	47.3	49.3
Marshall	17	57.5	27.9	52.9	68.9	28.4	51.5	9.8	23.3
	18	53.9	14.7	49.3	66.1	23.2	48.7	11.2	38.0
McCracken	19	35.7	32.3	31.1	60.1	19.6	42.7	15.1	9.9

Corn stover and winter wheat straw locations are assumed to be the same because they are coming from the same source. Based on the number of county locations identified in Table 4-30, the corn stover and winter wheat straw locations were selected by zooming in on each county and selecting areas which were highly dense in light yellow and/or light green. These areas were assumed to be fields, thus selected. Much effort was put into distributing the locations across the county as evenly as possible as seen in Fig. 4-8 (yellow tabs).

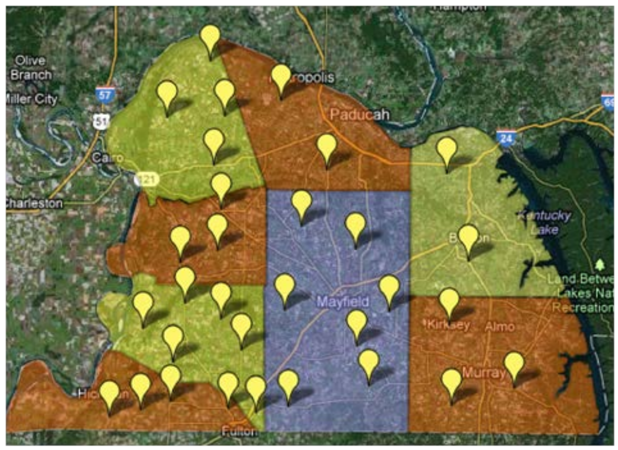


Figure 4-8: Corn stover and winter wheat straw locations

Distances from the corn stover and winter wheat straw locations to the potential biorefinery plant locations, provided in Table 4-33 below, were again determined using the directions feature in Google Maps.

Table 4-33: Distance from corn stover and winter wheat straw locations to biorefinery locations (miles)

County	Location	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Ballard	1	21.0	69.8	29.6	61.9	42.8	44.1	48.8	22.5
	2	8.7	72.3	17.2	49.6	39.7	32.1	53.6	28.1
	3	9.1	52.2	14.6	46.9	28.3	29.4	45.4	23.5
	4	15.3	62.6	23.9	56.2	37.0	38.8	44.0	18.4
Calloway	5	60.3	5.3	55.8	56.4	29.7	50.5	23.9	52.2
	6	50.1	9.7	45.6	55.1	19.5	40.7	15.9	34.6
	7	55.4	7.9	50.9	50.7	24.8	44.7	26.5	54.8
Carlisle	8	11.0	44.1	6.5	38.8	20.2	21.3	37.5	29.7
	9	14.7	46.7	6.2	35.8	22.8	18.3	40.1	34.1
	10	13.2	53.9	4.7	27.7	25.1	10.2	48.6	38.9
Fulton	11	42.9	51.9	34.3	3.4	39.4	19.4	58.5	68.5
	12	33.0	42.3	24.4	8.9	32.1	9.5	51.2	61.2
	13	37.6	48.0	29.1	5.7	37.8	14.2	56.9	66.9
	14	33.9	35.5	25.4	16.5	24.6	10.5	43.7	53.7
Graves	15	43.5	17.1	39.0	37.6	12.9	31.6	30.3	40.3
	16	42.3	26.4	33.7	24.8	20.6	18.9	39.6	49.7
	17	38.1	19.2	33.6	39.6	7.5	27.9	24.9	34.9
	18	23.0	36.6	18.4	52.4	12.7	28.6	29.3	20.0
	19	29.1	32.0	21.2	36.6	10.6	17.5	29.6	39.6
	20	30.7	30.3	26.2	49.4	7.7	32.0	20.8	18.8
	21	37.8	18.8	33.2	49.2	7.1	29.3	16.4	33.3
Hickman	22	38.5	31.7	30.0	21.6	19.8	15.1	38.9	48.9
	23	27.8	47.4	19.3	13.1	27.7	4.4	46.8	53.5
	24	24.7	44.6	16.1	23.7	20.7	6.2	41.6	41.5
	25	26.1	51.8	15.4	21.5	33.1	9.8	52.1	51.9
	26	18.6	48.6	10.1	22.3	28.2	4.8	47.2	44.3
	27	30.9	37.8	22.4	25.4	16.0	7.5	35.0	45.0
Marshall	28	50.3	15.1	45.7	61.7	20.5	44.3	4.9	32.0
	29	42.0	29.2	52.3	68.3	27.8	50.9	10.6	15.5
McCracken	30	24.7	56.3	25.2	57.6	31.6	40.1	37.6	11.3
	31	28.5	40.9	24.0	56.6	17.0	39.2	21.9	9.8

As shown in Fig. 4-8 below, the market distribution locations for electricity, gasoline, diesel, natural gas, and ethanol, shown as light blue tabs, were selected at major highway crossroads in each county seat. The selections of such locations were made so the transportation of the product could be accounted for. Only one market distribution location for each county has been identified due to the more dense population around these major highway crossroads compared to remaining population in each county. On the other hand, residual fuel oil (RFO) is not consumed by the general public in mass quantities. Therefore, it has been assumed RFO will be sold at conventional fuel terminals in the Jackson Purchase Region. Currently, there are two fuel terminals (IRS, 2012) located in McCracken County (Paducah) near the Ohio River as shown in with pink tabs in Fig. 4-9 below. Note natural gas will be transported to the market via pipeline. Therefore, the market distribution locations will serve as a consumption point assuming the natural gas will be supplied to various locations throughout the county via pipeline.

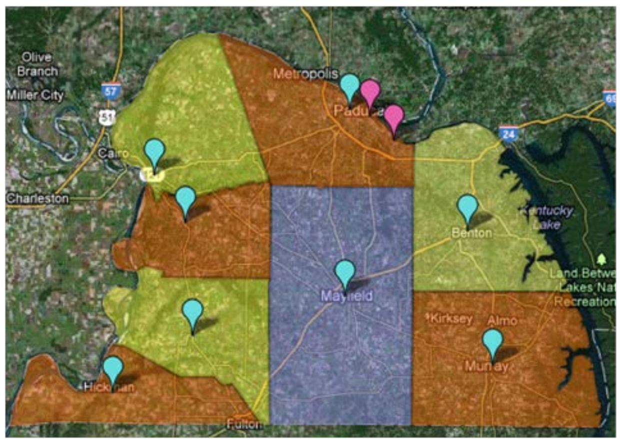


Figure 4-9: Market distribution locations

Distances from the potential biorefinery locations to the market distribution locations and residual fuel oil terminals as shown in Table 4-34 and Table 4-35, respectively, were determined again via the directions per Google Maps.

Table 4-34: Distance from the biorefinery locations to the market distribution locations (miles)

Location	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Ballard	0.4	54.7	8.9	41.3	30.8	23.8	48.1	32.1
Calloway	55.2	0.7	50.6	52.0	24.5	46.0	18.8	47.1
Carlisle	8.2	50.1	0.4	32.7	26.3	15.3	43.6	33.9
Fulton	42.2	51.5	33.6	0.9	39.8	18.7	58.9	68.9
Graves	31.8	23.7	27.3	40.9	0.7	22.2	20.7	29.9
Hickman	23.6	43.8	15.0	17.3	23.4	0.1	42.5	49.3
Marshall	49.0	18.8	44.4	60.5	20.0	43.0	0.8	24.2
McCracken	31.1	52.4	30.0	65.7	26.1	44.9	33.7	2.6

Table 4-35: Residual Fuel Oil Terminal Distances (miles)

Location	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
1	34.6	45.7	32.8	68.7	28.2	47.6	27.2	1.3
2	43.4	39.5	39.9	64.4	23.8	47.0	22.7	6.1

Given the distances from potential biorefinery locations and market distribution locations provided in Table 4-34 above, and electrical losses dependent on distance travelled (American Electric Power, 2012), the efficiency factors for supplying the electricity at the market distribution locations has been computed as shown in Table 4-36 below. For example, if the biorefinery were to be located in Ballard County and sending 100 kWh of electricity to Calloway County, only 95 kWh will be supplied for consumption in Calloway County due to 5 kWh being lost to the ambient surroundings during transportation.

Table 4-36: Electrical grid efficiencies

Location	Ballard	Calloway	Carlisle	Fulton	Graves	Hickman	Marshall	McCracken
Ballard	1.00	0.95	0.99	0.96	0.97	0.98	0.95	0.97
Calloway	0.95	1.00	0.95	0.95	0.98	0.95	0.98	0.95
Carlisle	0.99	0.95	1.00	0.97	0.97	0.98	0.96	0.97
Fulton	0.96	0.95	0.97	1.00	0.96	0.98	0.94	0.93
Graves	0.97	0.98	0.97	0.96	1.00	0.98	0.98	0.97
Hickman	0.98	0.96	0.99	0.98	0.98	1.00	0.96	0.95
Marshall	0.95	0.98	0.96	0.94	0.98	0.96	1.00	0.98
McCracken	0.97	0.95	0.97	0.93	0.97	0.96	0.97	1.00

Two different modeling scenarios have been carried out using the information described in this chapter with regards to biomass feedstock availability, product demand, locations and distance for the biomass, plant, and market distribution centers. The following chapter, Chapter 5, will discuss these scenarios in detail followed by the results & analysis in Chapter 6 as well as the discussion in Chapter 7.

5 MODELING SCENARIOS

The following sections will describe the integrated biorefinery conversion technology (5.1) and the fermentation conversion technology (5.2) in more detail. Any model input variables such as monthly feedstock availability and product demand, as well as any necessary communication between process models will be described and presented under their respective modeling scenario.

5.1 Integrated Biorefinery Conversion Technology

As shown in Fig. 5-1 below, the feedstock paired with the integrated biorefining (IBR) scenario are corn stover, forest residue, and poultry litter. The first step of the IBR process is gasification which the feedstocks will be processed (Tijmensen et al, 2002) for the creation of syngas, mainly comprising of carbon monoxide (CO) and hydrogen (H_2). The resulting stream is then sent to a water-gas shift reactor (Choi & Stenger, 2003) to improve the H_2:CO composition ratio where a portion of the hydrogen is then split for the creation of electricity, while the remaining products are sent for further processing via Fischer-Tropsch Synthesis (Zimmerman & Bukur, 1990) for the creation of gasoline, diesel, natural gas, and residual fuel oil.

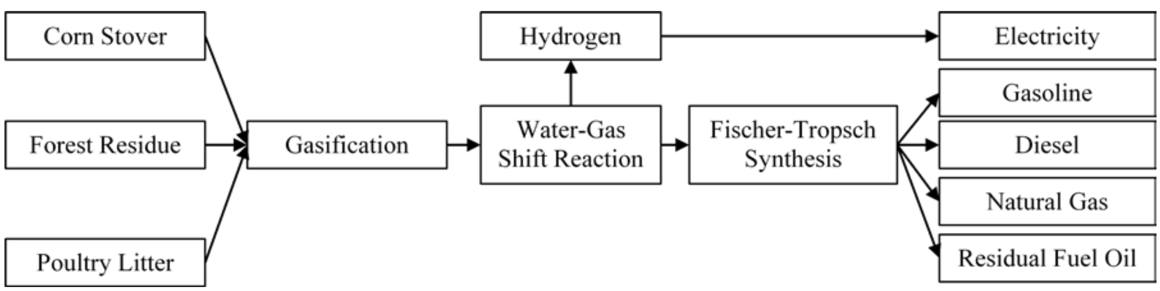


Figure 5-1: Integrated biorefining process flow diagram

5.1.1 Process Model Communication

Even though many models exist today involving these process steps, none consider this feedstock portfolio. Therefore, per the methodology in Chapter 3, a process simulation model was created in ASPEN Engineering Suite for the conversion of corn stover, forest residue, and poultry litter to the mentioned products above similar to the one created by Sukumara et al, (2012). Communication between the ASPEN process model and the MILP optimization model is outlined in Fig. 5-2 below. First, a range for the amount of feedstock is set to be used due to the Economic Optimizer feature within ASPEN being limited to liquids and gases (biomass is in the solid state) and a limited number of iterations. The process models were then completed by minimizing total utility costs: heating, cooling, and electricity costs. The amount of products created from the feedstock range was then generated to be used in the MILP optimization model as variable inputs. Given the product output, the process operating utility cost were further minimized through heat integration; a process utilizing hot and cold streams to heat and cool each other instead of using steam and cooling water for the same function, respectively. Given these outputs from the ASPEN process model, the location-allocation biorefinery supply chain problem was then solved through the MILP optimization model in ILOG OPL as described in Chapter 3. The resulting output from the MILP optimization model is then further analyzed, as highlighted in Chapter 6.

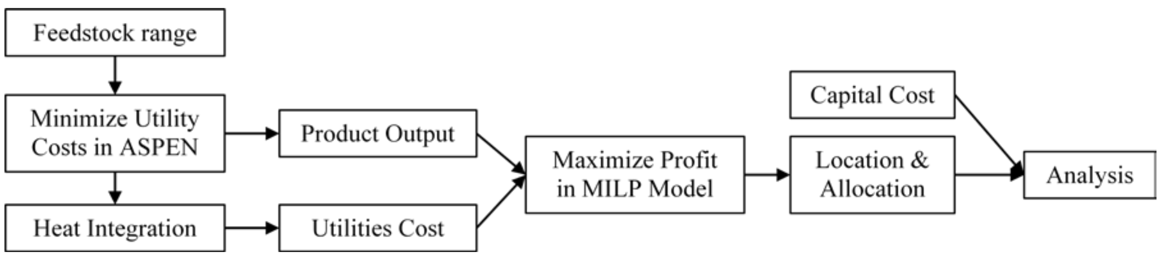


Figure 5-2: Process and optimization model communication

In Fig. 5-3 below is a screenshot of the process model in ASPEN Plus (part of the ASPEN Engineering Suite) representing the flow as outlined in Fig. 5-1.

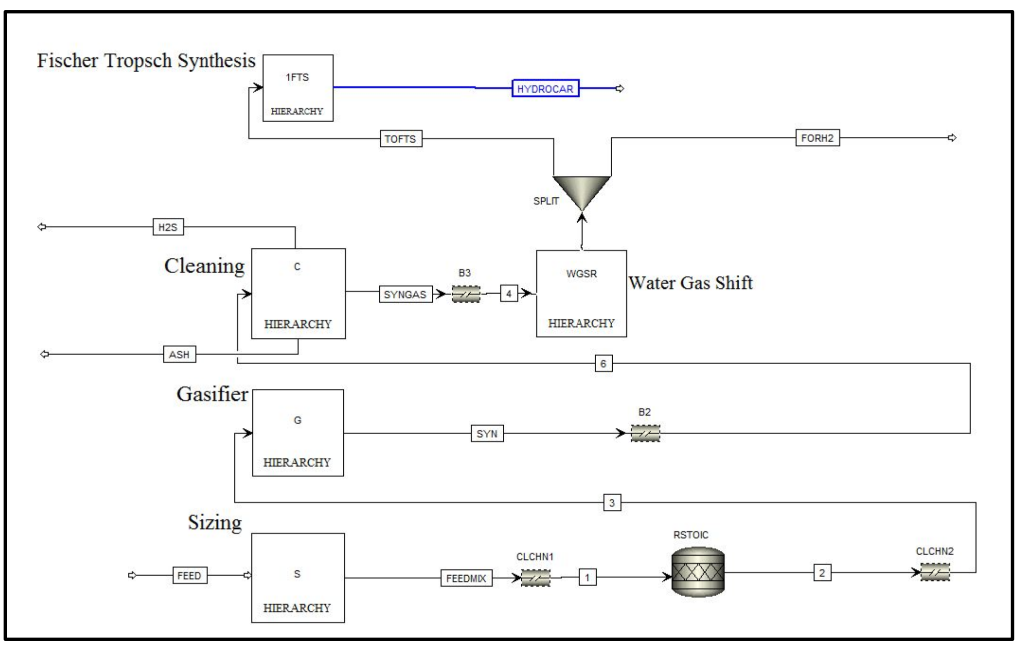


Figure 5-3: Integrated biorefining ASPEN screenshot

5.1.2 Feedstock Availability & Product Demand

Given the county feedstock monthly availability and the number of biomass locations in each respective county, the new supply of biomass for each county was then split evenly amongst the biomass locations. For instance, it has been decided that Ballard County has 4 corn stover locations with 4,772 tons available in the month of August. Therefore, 1,193 tons of corn stover will be newly supplied for each corn stover location in Ballard County for the month of August. This methodology has been applied for the new supply of biomass at each respective location in each county. Table 5-1, Table 5-2, and Table 5-3 show the monthly availability at each location from August to July for poultry litter, corn stover, and forest residue, respectively. The harvest of corn begins in August, thus, August will be the first month of the planning period to take full advantage of the fresh corn stover supply. Therefore, the numbers shown in the tables will be used as the new monthly supply variable (B_{fim}).

Given that only one market distribution location exists in each county (deemed as the county seat) for electricity, gasoline, diesel, and natural gas, it is assumed these locations will serve as the location for product demand for their respective county. Therefore, the county monthly demand for these products will be used as the product monthly demand variable (PD_{pjm}) as outlined in Table 4-23, 4-24, 4-25, and 4-26 for gasoline, diesel, natural gas, and electricity, respectively. However the demand for residual fuel oil at the terminals located in McCracken County (Paducah) is assumed to be unlimited due to residual fuel oil being used as bunker fuel oils in ships and barges along the Ohio River along with having other industrial applications.

Table 5-1: Poultry litter location monthly new supply (tons/month)

Location	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
1	1,660	1,607	1,660	1,607	1,660	1,660	1,500	1,660	1,607	1,660	1,607	1,660
2	1,085	1,050	1,085	1,050	1,085	1,085	980	1,085	1,050	1,085	1,050	1,085
3	1,085	1,050	1,085	1,050	1,085	1,085	980	1,085	1,050	1,085	1,050	1,085
4	1,549	1,499	1,549	1,499	1,549	1,549	1,399	1,549	1,499	1,549	1,499	1,549
5	1,232	1,192	1,232	1,192	1,232	1,232	1,112	1,232	1,192	1,232	1,192	1,232
6	1,662	1,608	1,662	1,608	1,662	1,662	1,501	1,662	1,608	1,662	1,608	1,662
7	1,662	1,608	1,662	1,608	1,662	1,662	1,501	1,662	1,608	1,662	1,608	1,662
8	1,662	1,608	1,662	1,608	1,662	1,662	1,501	1,662	1,608	1,662	1,608	1,662
9	1,662	1,608	1,662	1,608	1,662	1,662	1,501	1,662	1,608	1,662	1,608	1,662
10	1,662	1,608	1,662	1,608	1,662	1,662	1,501	1,662	1,608	1,662	1,608	1,662
11	1,662	1,608	1,662	1,608	1,662	1,662	1,501	1,662	1,608	1,662	1,608	1,662
12	1,662	1,608	1,662	1,608	1,662	1,662	1,501	1,662	1,608	1,662	1,608	1,662
13	1,662	1,608	1,662	1,608	1,662	1,662	1,501	1,662	1,608	1,662	1,608	1,662
14	1,662	1,608	1,662	1,608	1,662	1,662	1,501	1,662	1,608	1,662	1,608	1,662
15	1,644	1,591	1,644	1,591	1,644	1,644	1,485	1,644	1,591	1,644	1,591	1,644
16	1,644	1,591	1,644	1,591	1,644	1,644	1,485	1,644	1,591	1,644	1,591	1,644
17	1,644	1,591	1,644	1,591	1,644	1,644	1,485	1,644	1,591	1,644	1,591	1,644
18	1,644	1,591	1,644	1,591	1,644	1,644	1,485	1,644	1,591	1,644	1,591	1,644
19	1,644	1,591	1,644	1,591	1,644	1,644	1,485	1,644	1,591	1,644	1,591	1,644
20	1,644	1,591	1,644	1,591	1,644	1,644	1,485	1,644	1,591	1,644	1,591	1,644
21	1,399	1,353	1,399	1,353	1,399	1,399	1,263	1,399	1,353	1,399	1,353	1,399

Table 5-2: Corn stover location monthly new supply (tons/month)

Location	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
1	1,193	11,693	9,068	1,909	-	-	-	-	-	-	-	-
2	1,193	11,693	9,068	1,909	-	-	-	-	-	-	-	-
3	1,193	11,693	9,068	1,909	-	-	-	-	-	-	-	-
4	1,193	11,693	9,068	1,909	-	-	-	-	-	-	-	-
5	1,348	13,212	10,246	2,157	-	-	-	-	-	-	-	-
6	1,348	13,212	10,246	2,157	-	-	-	-	-	-	-	-
7	1,348	13,212	10,246	2,157	-	-	-	-	-	-	-	-
8	1,515	14,845	11,512	2,424	-	-	-	-	-	-	-	-
9	1,515	14,845	11,512	2,424	-	-	-	-	-	-	-	-
10	1,515	14,845	11,512	2,424	-	-	-	-	-	-	-	-
11	1,123	11,003	8,533	1,796	-	-	-	-	-	-	-	-
12	1,123	11,003	8,533	1,796	-	-	-	-	-	-	-	-
13	1,123	11,003	8,533	1,796	-	-	-	-	-	-	-	-
14	1,123	11,003	8,533	1,796	-	-	-	-	-	-	-	-
15	1,585	15,529	12,043	2,535	-	-	-	-	-	-	-	-
16	1,585	15,529	12,043	2,535	-	-	-	-	-	-	-	-
17	1,585	15,529	12,043	2,535	-	-	-	-	-	-	-	-
18	1,585	15,529	12,043	2,535	-	-	-	-	-	-	-	-
19	1,585	15,529	12,043	2,535	-	-	-	-	-	-	-	-
20	1,585	15,529	12,043	2,535	-	-	-	-	-	-	-	-
21	1,585	15,529	12,043	2,535	-	-	-	-	-	-	-	-
22	1,364	13,363	10,363	2,182	-	-	-	-	-	-	-	-
23	1,364	13,363	10,363	2,182	-	-	-	-	-	-	-	-
24	1,364	13,363	10,363	2,182	-	-	-	-	-	-	-	-
25	1,364	13,363	10,363	2,182	-	-	-	-	-	-	-	-
26	1,364	13,363	10,363	2,182	-	-	-	-	-	-	-	-
27	1,364	13,363	10,363	2,182	-	-	-	-	-	-	-	-
28	589	5,769	4,474	942	-	-	-	-	-	-	-	-
29	589	5,769	4,474	942	-	-	-	-	-	-	-	-
30	1,051	10,297	7,985	1,681	-	-	-	-	-	-	-	-
31	1,051	10,297	7,985	1,681	-	-	-	-	-	-	-	-

Table 5-3: Forest residue location monthly new supply (tons/month)

Location	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
1	368	356	368	356	368	368	332	368	356	368	356	368
2	368	356	368	356	368	368	332	368	356	368	356	368
3	368	356	368	356	368	368	332	368	356	368	356	368
4	368	356	368	356	368	368	332	368	356	368	356	368
5	309	299	309	299	309	309	279	309	299	309	299	309
6	309	299	309	299	309	309	279	309	299	309	299	309
7	412	398	412	398	412	412	372	412	398	412	398	412
8	412	398	412	398	412	412	372	412	398	412	398	412
9	412	398	412	398	412	412	372	412	398	412	398	412
10	412	398	412	398	412	412	372	412	398	412	398	412
11	412	398	412	398	412	412	372	412	398	412	398	412
12	223	216	223	216	223	223	201	223	216	223	216	223
13	306	296	306	296	306	306	276	306	296	306	296	306
14	306	296	306	296	306	306	276	306	296	306	296	306
15	306	296	306	296	306	306	276	306	296	306	296	306
16	278	269	278	269	278	278	251	278	269	278	269	278
17	390	377	390	377	390	390	352	390	377	390	377	390
18	390	377	390	377	390	390	352	390	377	390	377	390
19	170	164	170	164	170	170	153	170	164	170	164	170

5.1.3 Variable Inputs

For model inputs relating to costs, an extensive literature review was conducted as summarized in Table 5-4 below. To account for inflation, from the original values obtained from literature the current value was calculated using the US Department of Labor inflation calculator (US Dept. of Labor, 2012) to give their adjusted current value to be used as model inputs as shown in Table 5-4 below. The prices of products tend to fluctuate throughout the year. Therefore, the product prices were determined by examining the price range over the past year and assuming a reasonable well rounded estimate. For example, the price of regular gasoline and No. 2 diesel fuel from May 2011 to May 2012 had ranges of $3.23-$3.97 and $3.72-$4.14, respectively (EIA, 2012). Therefore, the prices of gasoline and diesel were assumed to be $3.50 and $4.00, respectively. This methodology was applied to obtain the prices of electricity, natural gas, and residual fuel oil.

Table 5-4: Integrated biorefining cost parameters summary

Cost Parameters	Original Value	Adjusted Value	Reference
Biomass Purchasing Costs			
Poultry Litter		$28.93/ton	
Cleanout cost	$7.42/ton	*$7.83/ton*	Jensen et al (2010)
Payment to farmer	$20/ton	*$21.10/ton*	Jensen et al (2010)
Forest Residue		$14.48/ton	
Delivered cost	$14.16/ton	*$14.48/ton*	Wu et al (2011)
Corn Stover		$33.21/ton	
Square baling	$22.81/ton	*$26.03/ton*	Sokhansanj et al (2006)
Payment to farmer	$6.80/ton	*$7.18/ton*	Morey et al (2010)
Storage Costs			
Local storage land rent	$0.397/ton	$0.42/ton	Morey et al (2010)
Transportation Costs			
Bulk Solids			
Time dependent	$29/hr/truck	$30.99/hr/truck	Tittman et al (2008)
Distance dependent	$1.2/mi/truck	$1.28/mi/truck	Tittman et al (2008)
Liquids			
Time dependent	$32/hr/truck	$34.20/hr/truck	Tittman et al (2008)
Distance dependent	$1.3/mi/truck	$1.39/mi/truck	Tittman et al (2008)
Diesel		$4.00/gall	
Biorefinery			
Skilled labor	$25.58/hr	$33.19/hr	Peters et al (2003)
Product Prices			
Gasoline		$3.50/gall	
Diesel		$4.00/gall	
Electricity		$70/MWh	
Natural Gas		$2.50/MMscf	
Residual Fuel Oil		$2.50/gall	

Table 5-5 below summarizes other parameter inputs for the integrated biorefining scenario with respective references. Given the weight limit for a vehicle in Kentucky is 80,000 pounds (KRS, 2004), the total weight of filled truck is assumed to be 75,000 pounds so that there are not any potential fines from regulators if trucks were to be overfilled by mistake. Assuming the typical truck weighs 35,000 pounds or 17.5 tons, the maximum amount of biomass or product to be transported is 40,000 pounds. The amount of corn stover to be transported in a truckload is 12.35 tons due to not being as dense as the other biomass feedstocks. The amount of product to be shipped per truck is based on the density of the product and the 40,000 pound limit.

Table 5-5: Integrated biorefining miscellaneous parameters

Other Parameters	Value	Reference
Biomass Transportation		
Poultry Litter	20 tons/truck	
Forest Residue	20 tons/truck	
Corn Stover	12.35 tons/truck	Shokhansaj et al (2010)
Biorefinery		
Labor Needed	.002 hrs/kg produced	Peters et al (2003)
Product Transportation		
Gasoline		
Truck capacity	20 tons/truck	
Volume	6,565 gall/truck	
Diesel		
Truck capacity	20 tons/truck	
Volume	5,050 gall/truck	
Residual Fuel Oil		
Truck capacity	20 tons/truck	
Volume	4,846 gall/truck	
Other		
Truck mass	17.5 tons/truck	
Diesel needed	0.2963 gall/ton-mi	

5.2 Fermentation Conversion Technology

A cost analysis completed by Kazi et al, (2010) determined that dilute acid pretreatment followed by enzymatic Saccharification and pentose/hexose co-fermentation using recombinant *Zymomnos molbilis* is the most economical way to produce ethanol from corn stover. Therefore this process has been chosen as the conversion technology for the production of ethanol from corn stover and winter wheat straw, as shown in Fig. 5-4 below. It is assumed that this conversion technology is also the most economical for winter wheat straw as well.

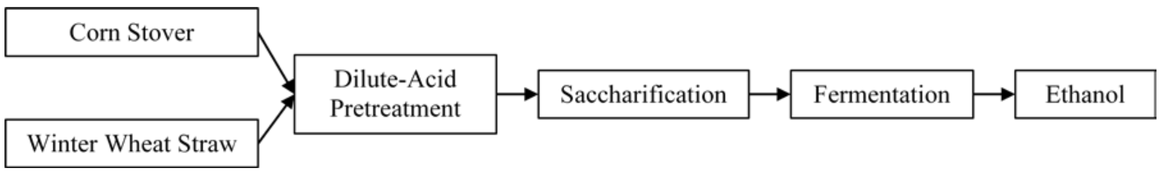


Figure 5-4: Fermentation process flow diagram

5.2.1 Feedstock Availability

As with the integrated biorefining scenario, the monthly new supply of biomass for each feedstock location was determined by equally splitting the county monthly availability to each feedstock location within that respective county. Table 5-6 and Table 5-7 below represent the new monthly supply of corn stover and winter wheat straw, respectively. The month of June was chosen as the first month of the planning period for this scenario to take full advantage of the supply of winter wheat straw since the winter wheat straw is first harvested beginning in the first week of June.

Table 5-6: Corn stover location monthly new supply (tons/month)

Location	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
1	-	-	1,193	11,693	9,068	1,909	-	-	-	-	-	-
2	-	-	1,193	11,693	9,068	1,909	-	-	-	-	-	-
3	-	-	1,193	11,693	9,068	1,909	-	-	-	-	-	-
4	-	-	1,193	11,693	9,068	1,909	-	-	-	-	-	-
5	-	-	1,348	13,212	10,246	2,157	-	-	-	-	-	-
6	-	-	1,348	13,212	10,246	2,157	-	-	-	-	-	-
7	-	-	1,348	13,212	10,246	2,157	-	-	-	-	-	-
8	-	-	1,515	14,845	11,512	2,424	-	-	-	-	-	-
9	-	-	1,515	14,845	11,512	2,424	-	-	-	-	-	-
10	-	-	1,515	14,845	11,512	2,424	-	-	-	-	-	-
11	-	-	1,123	11,003	8,533	1,796	-	-	-	-	-	-
12	-	-	1,123	11,003	8,533	1,796	-	-	-	-	-	-
13	-	-	1,123	11,003	8,533	1,796	-	-	-	-	-	-
14	-	-	1,123	11,003	8,533	1,796	-	-	-	-	-	-
15	-	-	1,585	15,529	12,043	2,535	-	-	-	-	-	-
16	-	-	1,585	15,529	12,043	2,535	-	-	-	-	-	-
17	-	-	1,585	15,529	12,043	2,535	-	-	-	-	-	-
18	-	-	1,585	15,529	12,043	2,535	-	-	-	-	-	-
19	-	-	1,585	15,529	12,043	2,535	-	-	-	-	-	-
20	-	-	1,585	15,529	12,043	2,535	-	-	-	-	-	-
21	-	-	1,585	15,529	12,043	2,535	-	-	-	-	-	-
22	-	-	1,364	13,363	10,363	2,182	-	-	-	-	-	-
23	-	-	1,364	13,363	10,363	2,182	-	-	-	-	-	-
24	-	-	1,364	13,363	10,363	2,182	-	-	-	-	-	-
25	-	-	1,364	13,363	10,363	2,182	-	-	-	-	-	-
26	-	-	1,364	13,363	10,363	2,182	-	-	-	-	-	-
27	-	-	1,364	13,363	10,363	2,182	-	-	-	-	-	-
28	-	-	589	5,769	4,474	942	-	-	-	-	-	-
29	-	-	589	5,769	4,474	942	-	-	-	-	-	-
30	-	-	1,051	10,297	7,985	1,681	-	-	-	-	-	-
31	-	-	1,051	10,297	7,985	1,681	-	-	-	-	-	-

Table 5-7: Winter wheat straw location monthly new supply (tons/month)

Location	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
1	3,816	2,480	64	-	-	-	-	-	-	-	-	-
2	3,816	2,480	64	-	-	-	-	-	-	-	-	-
3	3,816	2,480	64	-	-	-	-	-	-	-	-	-
4	3,816	2,480	64	-	-	-	-	-	-	-	-	-
5	7,260	4,719	121	-	-	-	-	-	-	-	-	-
6	7,260	4,719	121	-	-	-	-	-	-	-	-	-
7	7,260	4,719	121	-	-	-	-	-	-	-	-	-
8	2,700	1,755	45	-	-	-	-	-	-	-	-	-
9	2,700	1,755	45	-	-	-	-	-	-	-	-	-
10	2,700	1,755	45	-	-	-	-	-	-	-	-	-
11	3,218	2,091	54	-	-	-	-	-	-	-	-	-
12	3,218	2,091	54	-	-	-	-	-	-	-	-	-
13	3,218	2,091	54	-	-	-	-	-	-	-	-	-
14	3,218	2,091	54	-	-	-	-	-	-	-	-	-
15	4,675	3,039	78	-	-	-	-	-	-	-	-	-
16	4,675	3,039	78	-	-	-	-	-	-	-	-	-
17	4,675	3,039	78	-	-	-	-	-	-	-	-	-
18	4,675	3,039	78	-	-	-	-	-	-	-	-	-
19	4,675	3,039	78	-	-	-	-	-	-	-	-	-
20	4,675	3,039	78	-	-	-	-	-	-	-	-	-
21	4,675	3,039	78	-	-	-	-	-	-	-	-	-
22	3,015	1,960	50	-	-	-	-	-	-	-	-	-
23	3,015	1,960	50	-	-	-	-	-	-	-	-	-
24	3,015	1,960	50	-	-	-	-	-	-	-	-	-
25	3,015	1,960	50	-	-	-	-	-	-	-	-	-
26	3,015	1,960	50	-	-	-	-	-	-	-	-	-
27	3,015	1,960	50	-	-	-	-	-	-	-	-	-
28	4,194	2,726	70	-	-	-	-	-	-	-	-	-
29	4,194	2,726	70	-	-	-	-	-	-	-	-	-
30	3,096	2,012	52	-	-	-	-	-	-	-	-	-
31	3,096	2,012	52	-	-	-	-	-	-	-	-	-

5.2.2 Variable Inputs

From the literature review, supply chain costs were indentified from field to market for the production of ethanol from corn stover and winter wheat straw as summarized in Table 5-8 below. Information regarding the costs of winter wheat straw for the production of energy, fuels, and chemicals does not readily exist. Therefore, any costs and parameters associated with corn stover are assumed to be the same for winter wheat straw. Inflation was again accounted for through the use of the Department of Labor's inflation calculator. Operating costs were assumed to be linear based on a 56 million gallon per Humbird and Aden (2009). Maintenance costs were based on 10% of the installed equipment costs from the Humbird and Aden (2009) work. The price of ethanol was determined by using the ethanol wholesale price provided by EIA's Annual Energy Outlook (2012). Since the price of wholesale ethanol fluctuated around $2.50 per gallon, a price of $2.50 per gallon was used in the model.

Table 5-8: Fermentation cost parameters summary

Cost Parameters	Original Value	Adjusted Value	Reference
Biomass Purchasing Costs			
Corn Stover		$33.21/ton	
Square baling	$22.81/ton	*$26.03/ton*	Sokhansanj et al (2006)
Payment to farmer	$6.80/ton	*$7.18/ton*	Morey et al (2010)
Winter Wheat Straw		$33.21/ton	
Square baling	$22.81/ton	*$26.03/ton*	Sokhansanj et al (2006)
Payment to farmer	$6.80/ton	*$7.18/ton*	Morey et al (2010)
Storage Costs			
Local storage land rent	$0.397/ton	$0.42/ton	Morey et al (2010)
Transportation Costs			
Bulk Solids			
Time dependent	$29/hr/truck	$30.99/hr/truck	Tittman et al (2008)
Distance dependent	$1.2/mi/truck	$1.28/mi/truck	Tittman et al (2008)
Liquids			
Time dependent	$32/hr/truck	$34.20/hr/truck	Tittman et al (2008)
Distance dependent	$1.3/mi/truck	$1.39/mi/truck	Tittman et al (2008)
Diesel		$4.00/gall	
Biorefinery			
Fermentation operating	$0.671/gall	$0.72/gall	Humbird & Aden (2009)
Skilled labor	$25.58/hr	$33.19/hr	Engineering News Record (2001)
Maintenance costs	$0.281/gall	$0.301/gall	Humbird & Aden (2009)
Product Prices			
Ethanol		$2.50/gall	EIA (2012a)

Table 5-9 below represents the data regarding the miscellaneous input variables for the corn stover and winter wheat straw to ethanol scenario. The amount of ethanol to be shipped via truck was determined by the maximum weight allowance of 80,000 pounds (KRS, 2004), a buffer of 5,000 pounds, and the density of ethanol. The amount of winter wheat straw to be transported per truck is assumed to be the same as corn stover given that both are agricultural residues from major grain production.

Table 5-9: Fermentation miscellaneous parameters

Other Parameters	Value	Reference
Biomass Transportation		
Corn Stover	12.35 tons/truck	Shokhansaj et al (2010)
Winter Wheat Straw	12.35 tons/truck	
Biorefinery		
Labor Needed	.002 hrs/kg produced	Peter et al (2003)
Ethanol Yield		
Corn Stover	67.64 gall/ton	Lee et al (2007)
Winter Wheat Straw	67.81 gall/ton	Humbird & Aden (2009)
Product Transportation		
Ethanol		
Truck capacity	20 tons/truck	
Volume	6,060 gall/truck	
Other		
Truck mass	17.5 tons/truck	
Diesel needed	0.2963 gall/ton-mi	

The results and sensitivity analysis from the integrated biorefining and fermentation case studies will be presented in Chapters 6 and 7, respectively, followed by a discussion of the supply chain performance in Chapter 8.

6 INTEGRATED BIOREFINING RESULTS & ANALYSIS

This chapter will present a detailed report of the results from the integrated biorefining scenario (6.1), as well as any potential decisions to improve the supply chain performance (6.2), along with a sensitivity analysis on the main parameters from the model outputs (6.3)

6.1 Integrated Biorefinery Results

Per the methodology and process model communication flow described in Chapter 3 and Chapter 5, respectively, a product slate was created in ASPEN Plus by minimizing utility costs via heat integration using all available biomass. Outputs from the ASPEN Plus models were then used as inputs for the MILP optimization model and solved using OPL ILOG CPLEX. using a personal laptop computer with an Intel Centrino processor and a clock speed of 2.00 GHz. Each model took approximately 85 seconds to solve.

6.1.1 Supply Chain Configurations

From the created product slate and feedstock requirements using all biomass, the resulting annual supply chain profitability came to a loss of roughly $70 million without a single profitable operating month, locating the biorefinery in Graves County (Mayfield). Therefore, an additional constraint was placed in the ASPEN Plus process model for the minimum and maximum monthly amount of each feedstock to be used for three different plant sizes. The monthly range of feedstock to be used corresponded to 1-10%, 10-15%, and 15-20% of monthly biomass availability for the small, medium, and large plant sizes, respectively, as shown in Table 6-1 below. Since only 5% of the total amount of corn stover is available in August, a smaller amount based on availability is to be used for corn stover. For the remaining months, September through July, the remaining 95% of total corn stover supply was evenly spread out across the months to serve as a basis for the amount to be used for the production of gasoline, diesel, natural gas, electricity, and residual fuel oil. The total amount of forest residue and poultry litter is assumed constant throughout the year (monthly amount based on the number of days in the month), therefore the daily amount to be used for each plant size will be the same from August to July. The resulting feedstock requirements and product slate created from the ASPEN Plus process models are shown in the Appendix for each plant size.

Table 6-1: ASPEN monthly feedstock range based on plant size (kg/s)

Month	August			September-July		
Feedstock	Corn Stover	Forest Residue	Poultry Litter	Corn Stover	Forest Residue	Poultry Litter
Small	0.1 - 2.5	0.1 - 0.5	0.1 - 2.0	0.1 - 4.5	0.1 - 0.5	0.1 - 2.0
Medium	2.5 - 3.75	0.5 - 0.75	2.0 - 3.0	4.5 - 6.75	0.5 - 0.75	2.0 - 3.0
Large	3.75 - 5.0	0.75 - 1.0	3.0 - 4.0	6.75 - 9.0	0.75 - 1.0	3.0 - 4.0

Figure 6-1, Fig. 6-2, and Fig. 6-3 represents the supply chain configurations for the small, medium, and large plants, respectively, consisting of feedstock (yellow, green, and blue tabs), biorefinery (red tab), residual fuel oil terminal (light blue tab), and market distribution locations (light blue tabs). As the size of the biorefinery increases, the number of feedstock and market distribution locations increase. Therefore, by supplying biomass and sending products to and from the biorefinery, respectively, higher supply chain costs will be seen. All three plants have been located in Hickman County (Clinton), while market distribution location include Hickman County (Clinton), Carlisle County (Bardwell), and Fulton County (Hickman) as well a residual fuel oil terminal in McCracken County (Paducah).

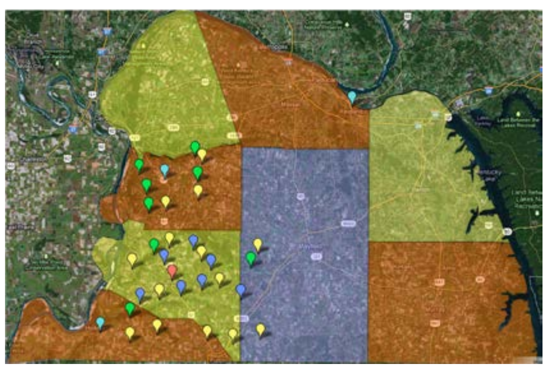


Figure 6-1: Large integrated biorefinery supply chain configuration

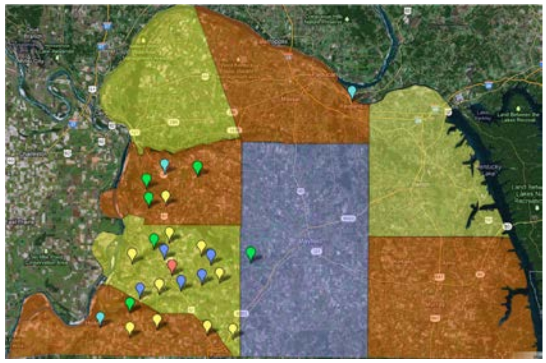


Figure 6-2: Medium integrated biorefinery supply chain configuration

Figure 6-3: Small integrated biorefinery supply chain configuration

Throughout the year for each biorefinery size, the same respective forest residue and poultry litter locations supply the biorefinery, whereas, the location from which the corn stover is supplied differs from month-to-month based on availability at each respective location. Therefore, as supply depletes from corn stover location close to the biorefinery, corn stover is then sent from farther distances, thus increasing biomass transportation costs.

6.1.2 Biorefinery Profitability, Costs, & Revenues

The monthly profitability from August to July for each plant size is shown in Fig. 6-4 below. From the parameters of the three plant sizes given by either the ASPEN process model, literature, or existing data, none of the plants are profitable in any given month throughout the year. The total losses for the year are $2.6 million, $7.2 million, and $13.3 million for the small, medium, and large biorefinery, respectively. For each plant size the losses decrease from August to September due to the corn stover becoming more readily available throughout the supply locations. Therefore, a decrease in transportation costs is seen as more corn stover is being transported from closer sources. As corn stover biomass depletes throughout the year, corn stover is then sent from farther distances, thus increasing biomass transportation costs for all three plant sizes.

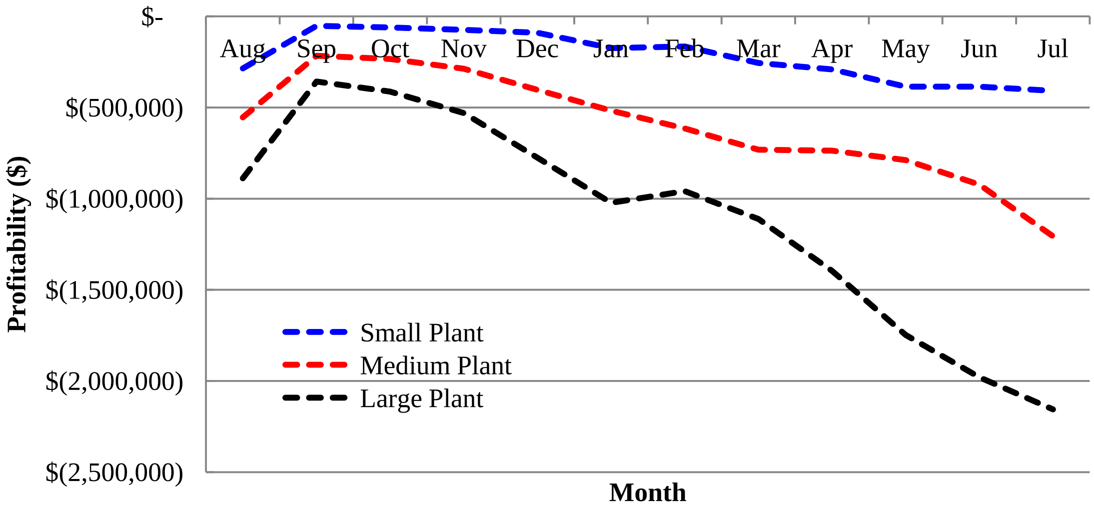
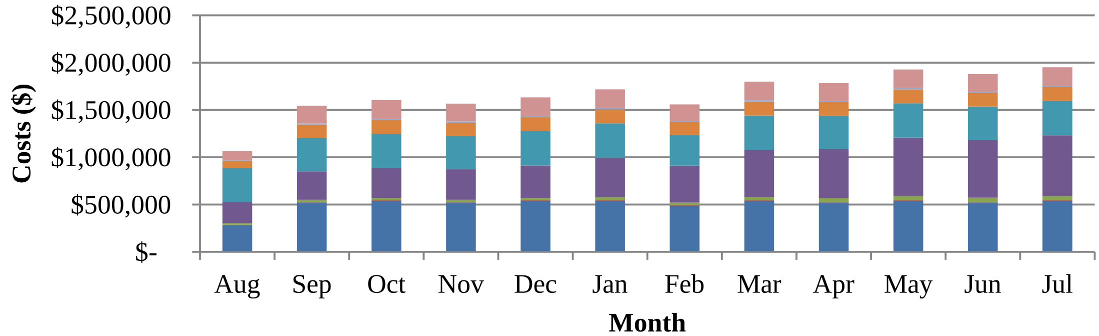
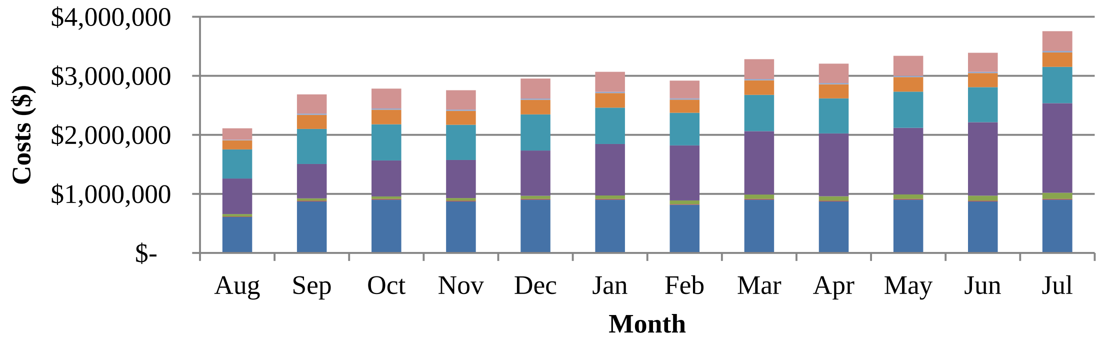


Figure 6-4: Integrated biorefinery supply chain monthly profitability for small, medium, and large plant sizes

Before additional decisions are made to improve the supply chain performance, the monthly costs and revenue streams must be evaluated for each respective plant size. The monthly cost breakdown is shown in Fig. 6-5a, Fig. 6-5b, and Fig. 6-5c, respectively for the small, medium, and large plant sizes. The majority of the costs for each plant size derive from the purchasing of biomass, utilities at the biorefinery, and diesel costs relating to transporting the biomass and products. The costs related to paying the employees at the plant and truck drivers as well as the land rent costs do not play a significant role in the monthly profitability for each plant size.



(a)



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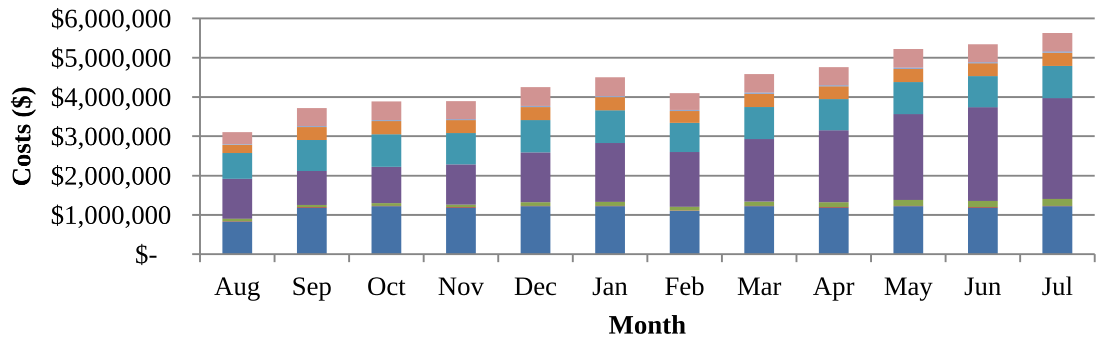
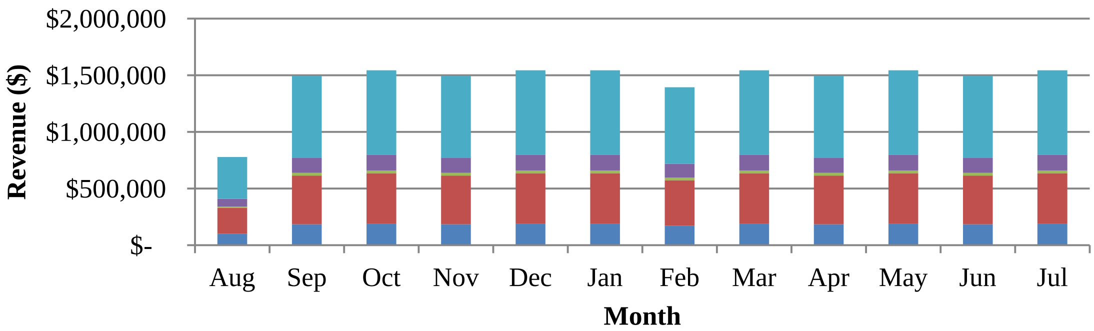


(c)

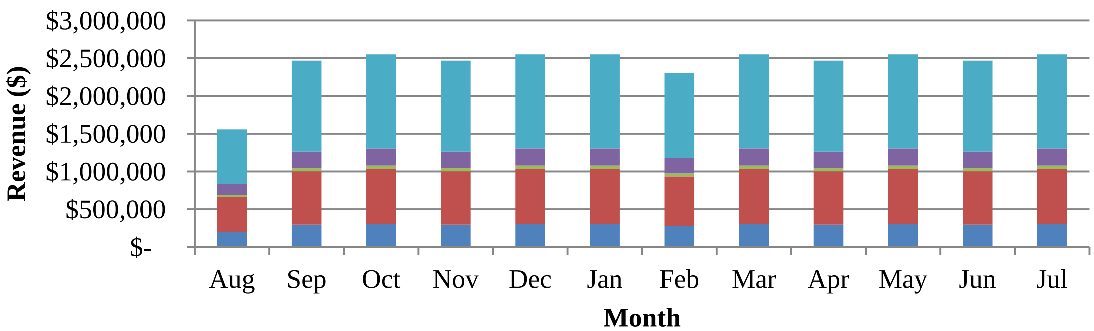
Product Transportation Diesel Costs
Product Transportation Truck Costs
Biorefinery Manpower Costs
Biorefinery Utilities Costs
Biomass Transportation Diesel Costs
Biomass Transportation Truck Costs
Biomass Land Rent Costs
Biomass Purchase Costs

6-5: Integrated biorefinery monthly costs ($/month), (a) small, (b) medium, and (c) large

The monthly revenue streams from electricity, gasoline, diesel, natural gas, and residual fuel oil are broken down by month in Fig. 6-6a, Fig. 6-6b, and Fig. 6-6c, respectively for the small, medium, and large plant sizes. For each plant size roughly 48% and 29% come from the sale of residual fuel oil and diesel, respectively. The remaining 23% of revenue is generated through the sale of gasoline, natural gas, and electricity.



(a)



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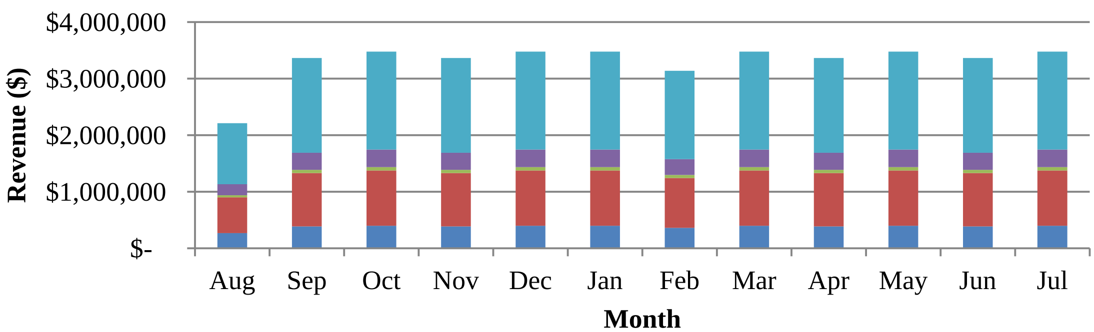

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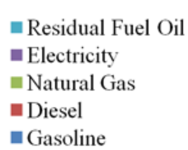


6-6: Integrated biorefinery monthly revenues ($/month), (a) small, (b) medium, and (c) large

6.2 Integrated Biorefining Additional Decisions

Due to each plant size not being profitable in any month throughout the year, additional decisions need to be made to improve the supply chain performance for each respective plant size. Since residual fuel oil makes up roughly 48% of the monthly revenue stream for each plant size and transportation of the residual fuel oil to the terminal ranges from 7.8% to 11.2% of the total monthly costs, a different mode of transporting the residual fuel oil is needed. When negating this cost, each plant has profitable months as shown in Fig. 6-7 below. It is assumed the cost of transporting the residual fuel oil is placed on a third party or transported via pipeline at a fraction of the cost. Since multiple pipelines exist in the region, this is not a far reaching assumption.

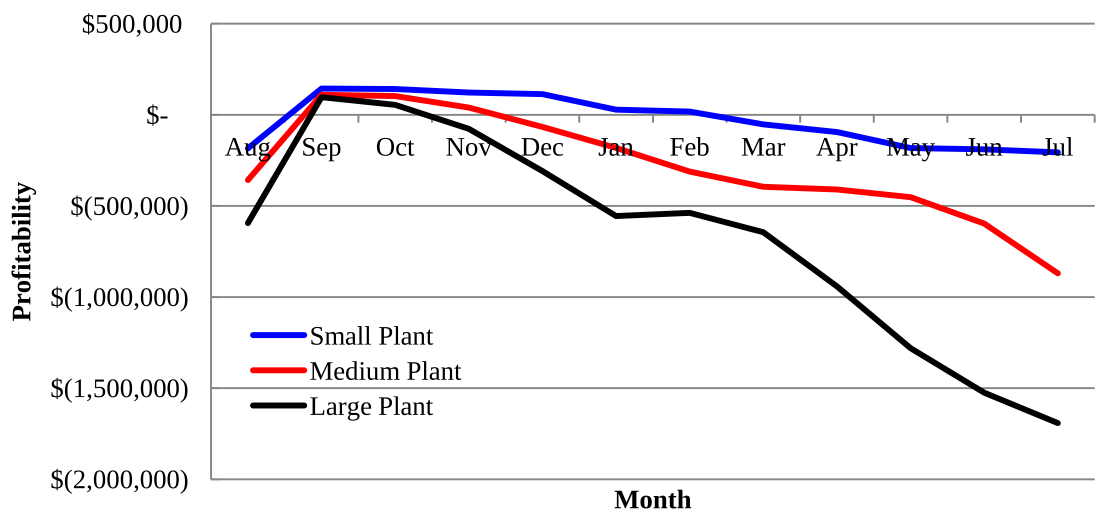


Figure 6-7: Monthly profitability without residual fuel oil transportation ($/month)

There has been much debate over the issue of government subsidies for the production of energy from biomass resources, especially ethanol from corn grain. However, subsidies are typically paid to the energy producer, thus indirectly to the farmer or aggregator for the particular biomass feedstock. Figure 6-8 below represents the monthly supply chain profitability given a government subsidy of $7 per ton paid directly to the farmer alleviating part of the biomass purchasing costs to the biorefinery. Note that RFO in Fig. 6-8 below represents residual fuel oil. The performance for each plant size as well as the implications of transporting or not transporting residual fuel oil is shown below. By alleviating a portion of the biomass purchasing costs by subsidizing the farmer or aggregator directly not only does the monthly supply chain performance for each plant size improve but also incentivizes other potential farmers or aggregators, thus, an increase in supply is expected. Therefore, costs associated with transporting such biomass should decrease as supply increase.

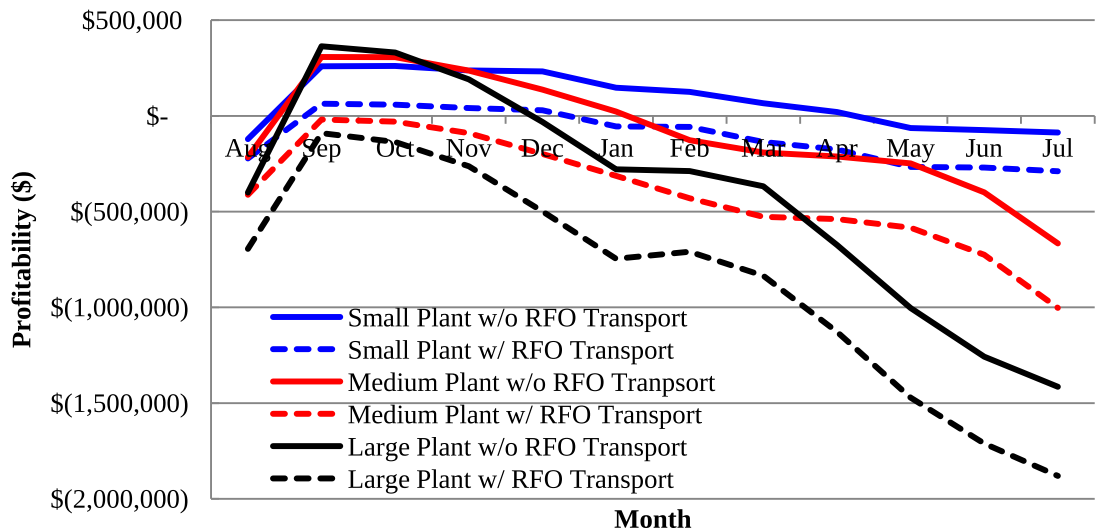


Figure 6-8: Monthly profitability with government subsidy to farmer ($/month)

Since governmental subsidies are out of the biorefinery's operational control for potential additional revenue whether that be indirectly from revenue streams, the focus here will be on improving supply chain performance without any government incentives. Therefore, an additional decision will be on shutting down production during the non-profitable months where residual fuel oil transported via truck is negated as shown in Fig. 6-9 below. The operating months for the small, medium, and large plants are August through January, August through October, and August to September, respectively.

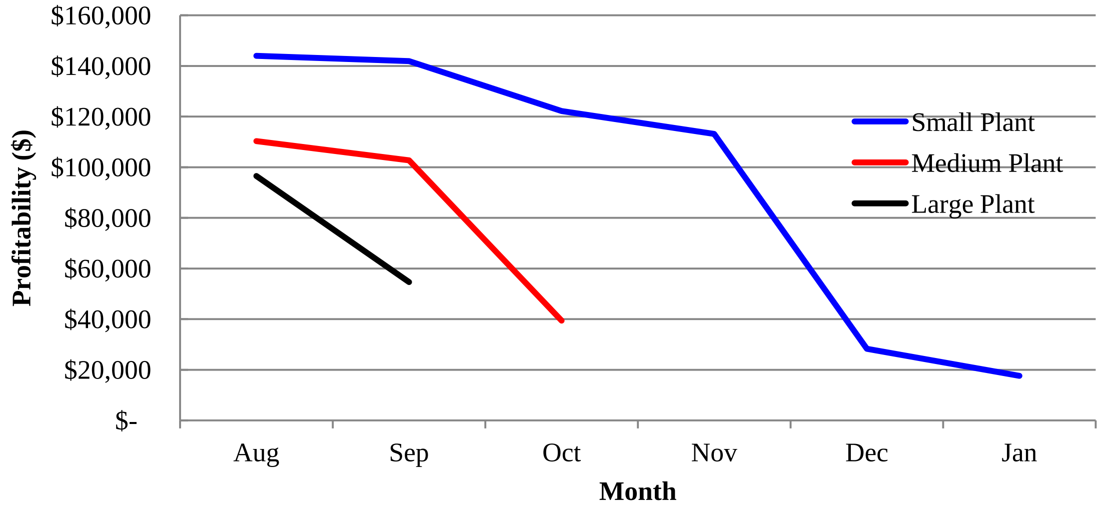


Figure 6-9: Monthly profitability with plant shutdown ($/month)

6.3 Integrated Biorefinery Sensitivity Analysis

Given the total profitability from Fig. 6-9 above, sensitivity analysis was conducted ranging the price of gasoline, diesel, natural gas, electricity, and residual fuel oil as shown in Fig. 6-10, Fig. 6-11, Fig. 6-12, and Fig. 6-13, respectively. The price ranges analyzed are $2.50-$4.25 per gallon of gasoline, $3.00-4.75 per gallon of diesel, $1.50-$3.25 per MSCF (thousand standard cubic feet) for natural gas, $55-$90 per MWh (megawatt-hour), and $1.50-$3.25 per gallon of residual fuel oil.

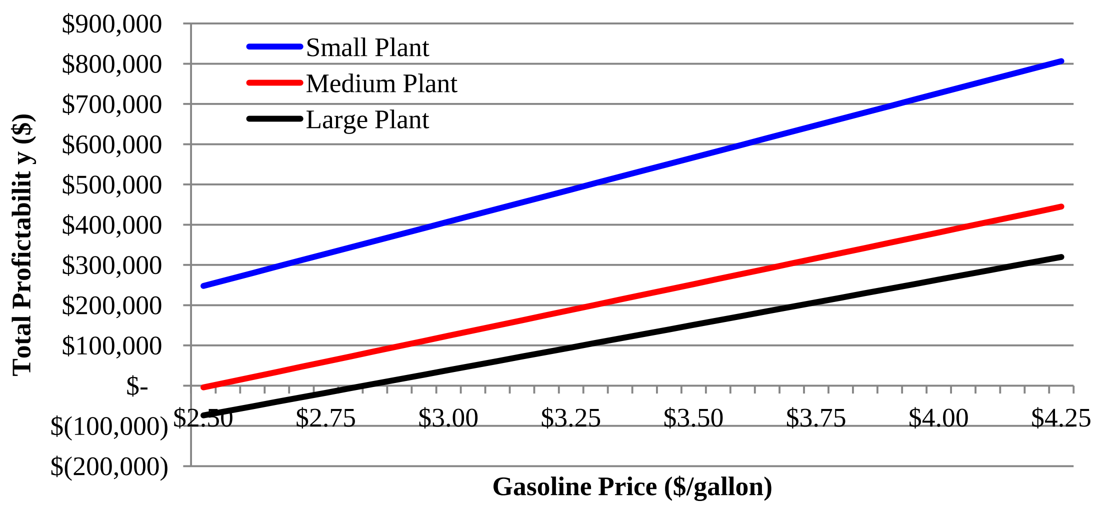


Figure 6-10: Annual profitability with ranging gasoline price ($/year)

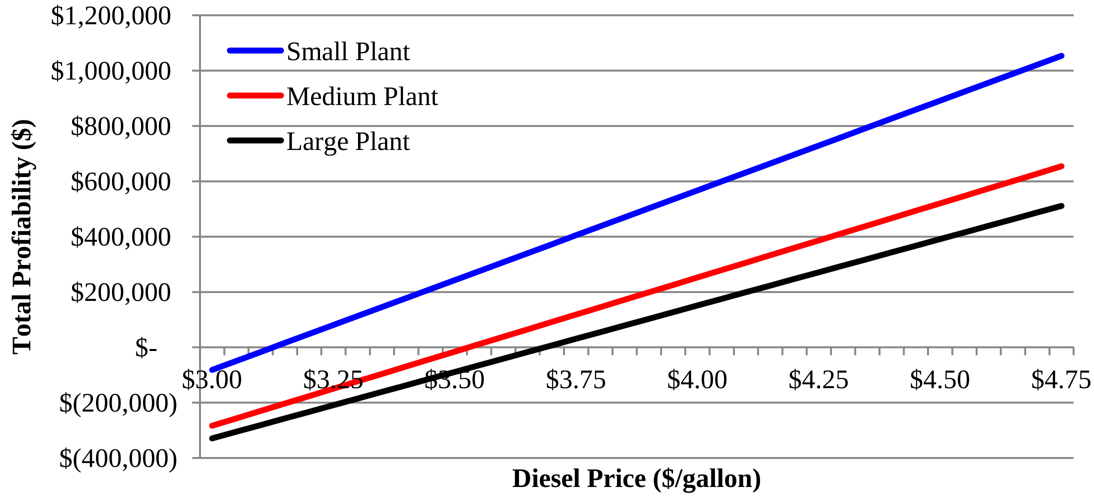


Figure 6-11: Annual profitability with ranging diesel price ($/year)

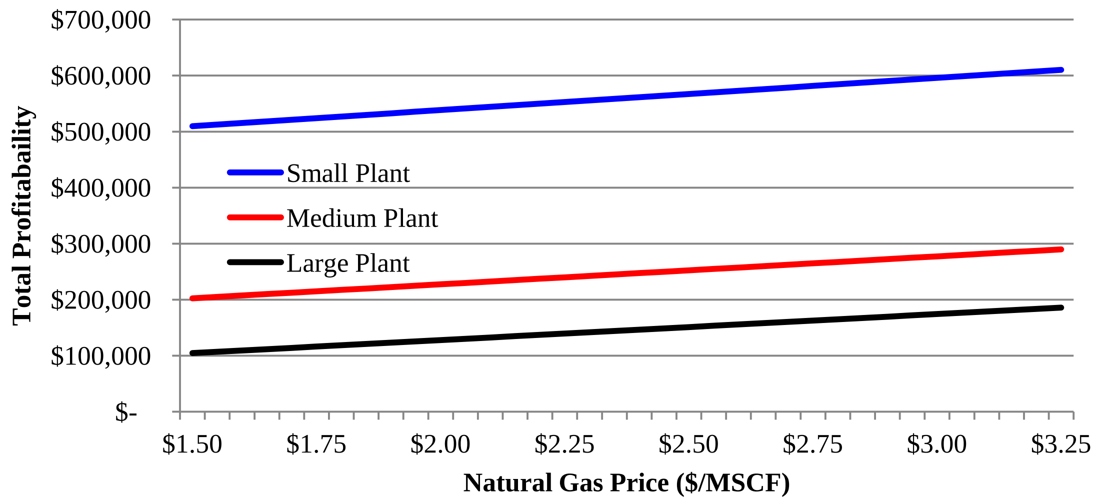


Figure 6-12: Annual profitability with ranging natural gas price ($/year)

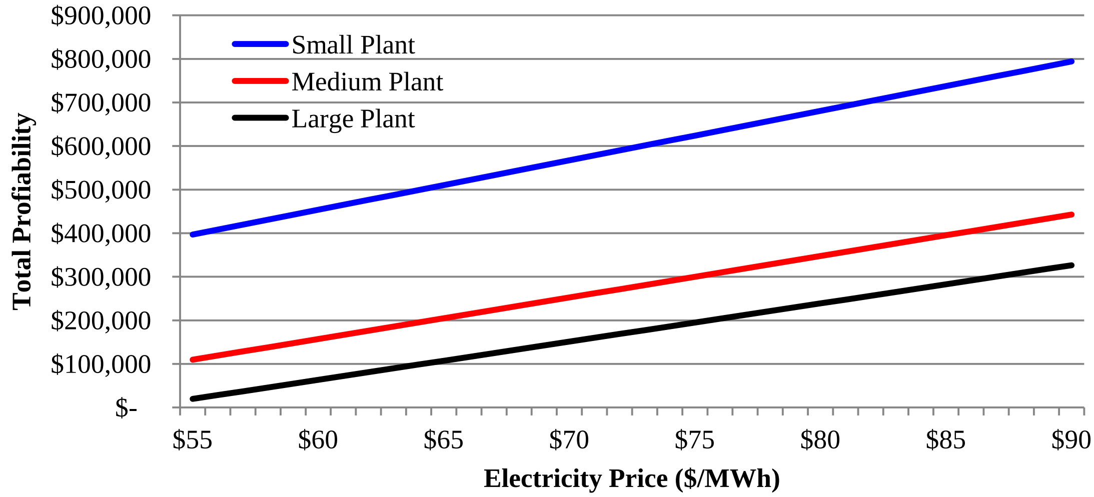


Figure 6-13: Annual profitability with ranging electricity price ($/year)

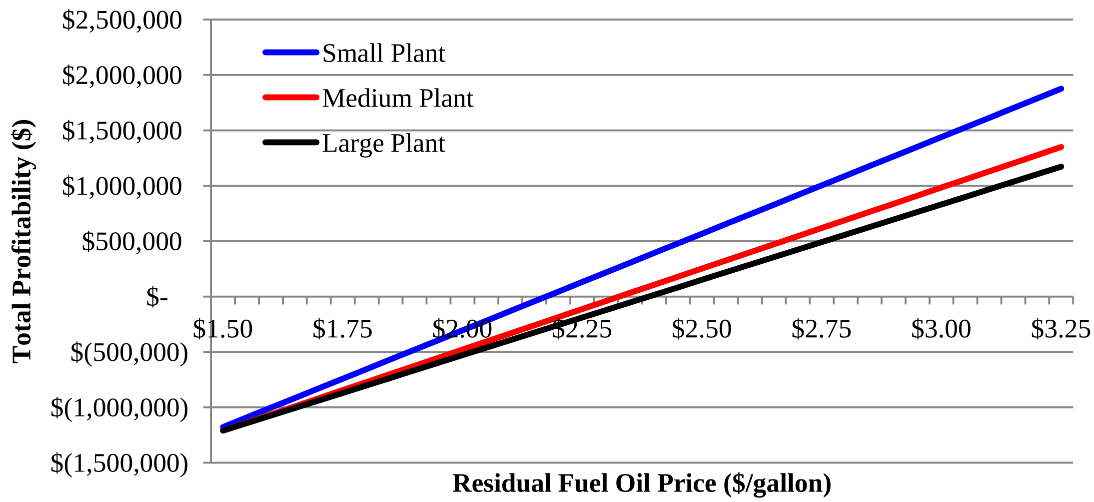


Figure 6-14: Annual profitability with ranging residual fuel oil price ($/year)

From the sensitivity analysis it is apparent the prices of diesel and residual fuel oil have the largest impact on supply chain profitability due to not only using diesel for the transportation of biomass and certain products but also diesel and residual fuel oil make up 29% and 48% of the monthly revenue stream for each plant size. The price of gasoline, natural gas, and electricity do not have large impacts on the supply profitability due to comprising of 23% of the monthly revenue stream. None of the plants are profitable when the price of diesel or residual fuel oil drops below $3.10 and $2.10 per gallon, respectively. Each plant size is profitable given the ranges for the price of electricity and natural gas, whereas, none of the plant sizes are profitable for a gasoline price below $3.15 per gallon for gasoline. Even though each plant is highly dependent on the price of diesel and residual fuel oil, the smaller plant size is more robust as it is profitable over a longer period of time as well as profitable over a broad range of prices for the given products. Due to diesel being the fuel used to transport both feedstocks and products, the effect on the supply chain performance from price of diesel is expected and typical.

The following chapter will present the results from the fermentation modeling scenario as well as a sensitivity analysis of each respective supply chain configuration. A more detailed discussion regarding the outcomes of each scenario will be given in Chapter 8.

7 FERMENTATION RESULTS & ANALYSIS

This chapter presents the results from the Fermentation modeling scenario obtained from the MILP optimization model using corn stover and winter wheat straw for the production of ethanol (7.1). A sensitivity analysis has been conducted to assess the robustness of each respective supply chain (7.2) for further discussion.

7.1 Fermentation Results

Since past process work involves corn stover and winter wheat straw for the production of ethanol, there is not a need to create a process simulation model. From the parameters given in Chapter 5, the MILP optimization model was then solved in ILOG OPL using a personal laptop computer with an Intel Centrino processor and a clock speed of 2.00 GHz. Each model took approximately 11 seconds to solve.

Per the methodology in Chapter 3, all available corn stover and winter wheat straw was used for the production of ethanol to provide a baseline for comparison against other potential plant sizes. Although the integrated biorefinery scenario required a supply of each biomass feedstock throughout the year, this is not the case with the fermentation scenario as existing process modeling already exists for this feedstock-to-product pathway. Therefore, only the months from June to November will have any ethanol production for the 'all-biomass' case due to these months being the only months that have new feedstock supply. Thus, all new biomass feedstock supply is used for the production of ethanol in each month. Hence, no costs or streams of revenue were seen from December through May due to not having a new supply of corn stover or winter wheat straw. The results from the MILP optimization model, using all the biomass, located a 68.6 million gallon plant in Graves County with an annual loss of $17.8 million without a single profitable month.

7.1.1 Supply Chain Configurations

Due to prior work being completed for this feedstock-to-product pathway and an annual loss of $17.8 million using all the biomass, three plant sizes were selected for further analysis. First, an additional decision variable was added to the MILP optimization model considering the plant size assuming constant production throughout the year (monthly amount produced dependent on number of days in the month) to provide a baseline for further comparison. From the optimal plant size found (1.89 million gallons) via the MILP optimization model, a larger and a smaller plant size were determined to be 0.5 million gallons and 5 million gallons, respectively.

By using the plant size as an additional decision variable, the model was then solved by maximizing profit resulting in a 1.89 million gallon capacity plant located in Calloway County as shown in Fig. 7-1 below. Only one supply location is needed throughout the year to supply the 1.89 million gallon biorefinery. The ethanol production at the biorefinery is sufficient enough to supply most, if not all of the monthly ethanol demand throughout the year in Calloway County (10% of gasoline monthly demand) as well as part of the monthly ethanol demand in Marshall County during August, October, January, March, and May. Note that the red, yellow, and light blue tabs in Fig. 7-1 below represent the biorefinery location, biomass location, and market distribution location, respectively. Also, the county in which the biorefinery is located also has a market distribution location but is not shown in the map due to covering up the location of the biorefinery. For example, in Fig. 7-1 below, the supply chain configuration below has two market distribution locations: one in Calloway County and the other in Marshall County.

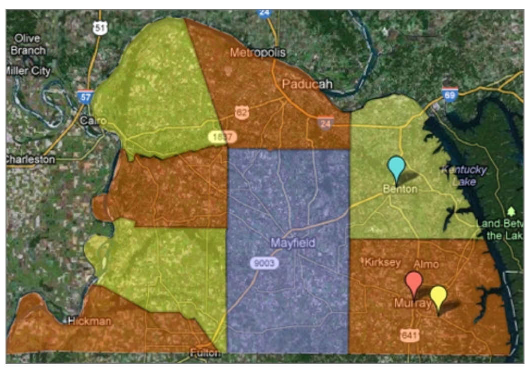


Figure 7-1: 1.89 Million gallon biorefinery supply chain configuration (optimal)

After optimizing the location-allocation as well as the plant size for an ethanol producing biorefinery supply chain, the plant size was then set for comparison to an annual capacity of 0.5 million gallons assuming constant production throughout the year (monthly production based on number of days in month). The MILP location-allocation optimization model was then solved locating the biorefinery in Fulton County as shown in Fig. 7-2 below. Again, only one feedstock location is needed to supply the 0.5 million gallon biorefinery throughout the year. The monthly production of ethanol at the biorefinery is enough to supply most, if not all of the monthly ethanol demand of Fulton County as well as part of the ethanol demand in Hickman County in June and July.

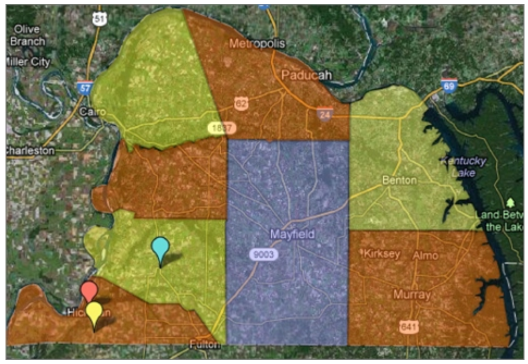


Figure 7-2: 0.5 Million gallon biorefinery supply chain configuration

An annual plant capacity was then set to 5.0 million gallons so that the performance of a larger biorefinery supply chain could be compared against the optimal supply chain with a annual plant capacity of 1.89 million gallons. The MILP location-allocation optimization model was then solved resulting with a biorefinery located in Calloway County as shown in Fig. 7-3 below with the respective supply chain configuration. Three feedstock locations are needed to supply the biorefinery with corn stover and winter wheat straw throughout the year. Given the constant supply of ethanol, the monthly amount of ethanol produced is adequate enough to supply all of the ethanol demand in Calloway County and Marshall County, as well as a partial amount of the demand in Graves County throughout the year. Market distribution locations in McCracken County and Hickman County are supplied during the month of January.

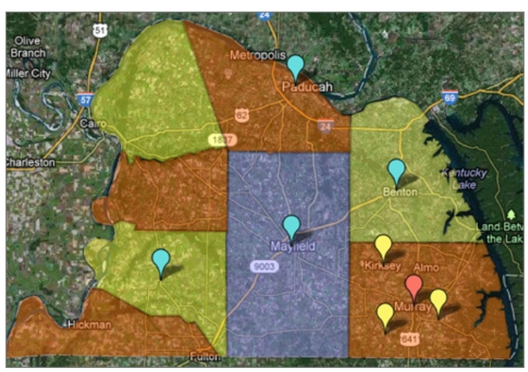


Figure 7-3: 5.0 Million gallon biorefinery supply chain configuration

7.1.2 Biorefinery Profitability, Costs, & Revenue

The monthly profitability from June to May for each plant size is shown in Fig. 7-4 below. From the parameters of the three plant sizes, an overall annual profit is seen for the 1.89 million gallon and 0.5 million gallon plant as well as being profitable in every month. However, the 5.0 million gallon plant is not profitable over the year nor is it profitable in any single month during that year. The yearly total profits for the 0.5 million gallon, 1.89 million gallon, and 5.0 million gallon plants are $125,695/year, $175,490/year, and $-722,237/year, respectively. The monthly profitability throughout the year remains fairly constant for the 0.5 million gallon and 1.89 million gallon plants, whereas, the monthly losses for the 5.0 million gallon plant varies drastically. Even though the monthly loss is around $20,000 per month for five months out of the year, it is coupled with losses of $80,000 plus per month in June and from January through May. Therefore, the 1.89 million gallon plant has the highest overall annual profitability due to a steady monthly profit range of $10,716-$16,314/month. The smaller plant size, 0.5 million gallons, also follows the 1.89 million gallon plant profitability trend over the course of the year as the profits range from $6,174-$7,410 per month.

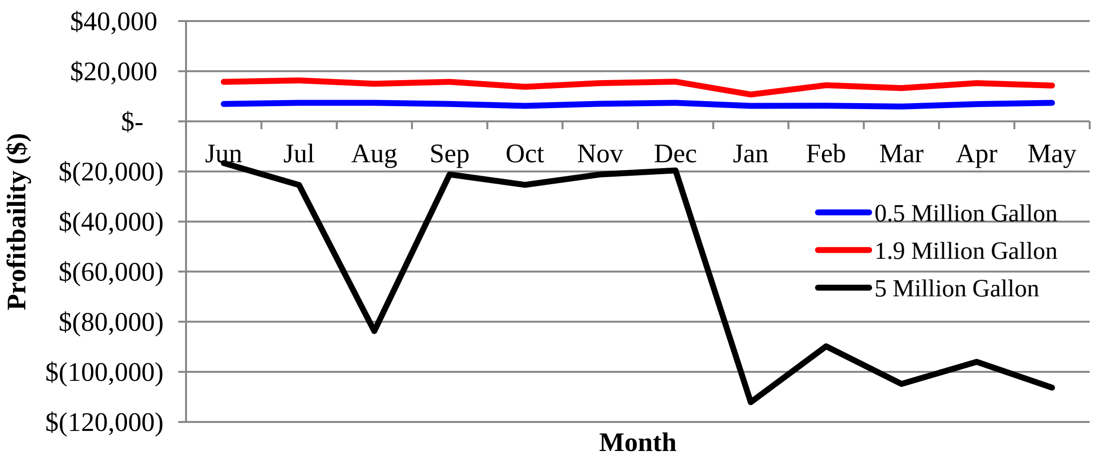


Figure 7-4: Fermentation biorefinery supply chain monthly profitability ($/month)

Even though the overall profitability for the 1.89 million gallon plant is greatest amongst the three plant sizes over a year, the monthly profits per gallon produced is greatest for the 0.5 million gallon capacity plant as shown in Fig. 7-5 below. The monthly profitability based on production for the 0.5 million gallon plant and 1.89 million gallon plant range from $0.14-0.17 per gallon and $0.07-0.10 per gallon, respectively.

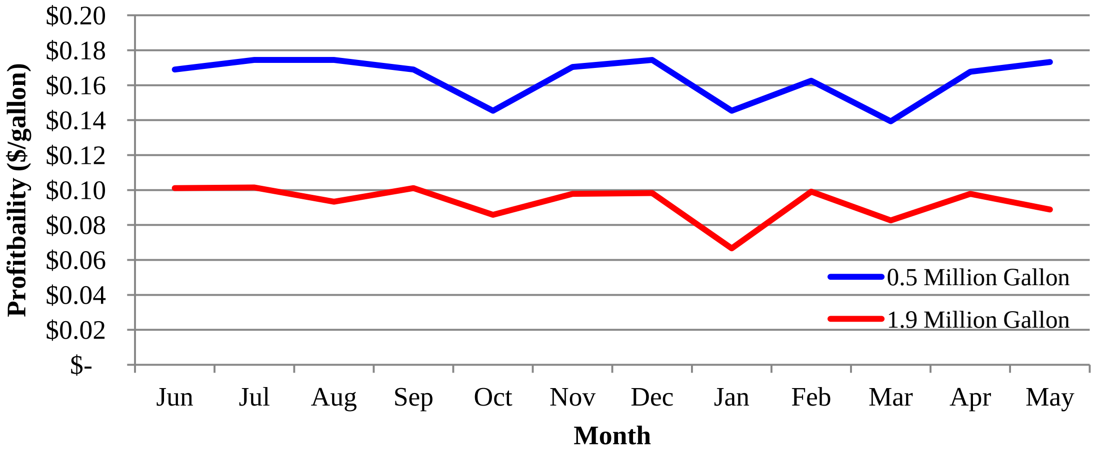
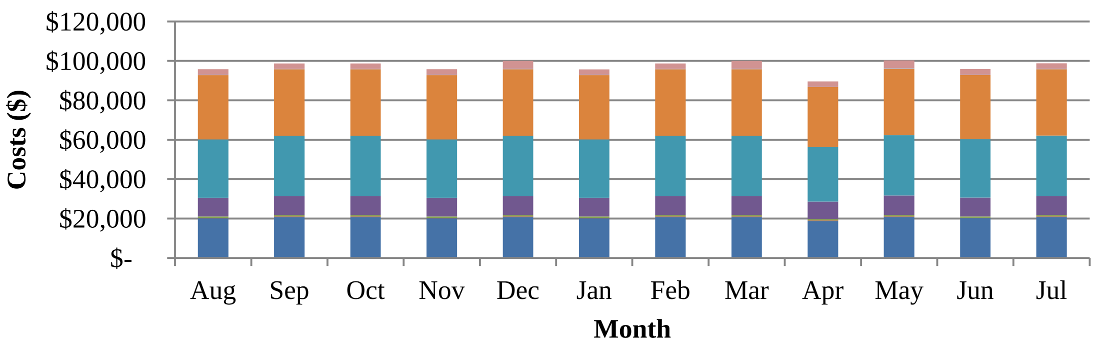
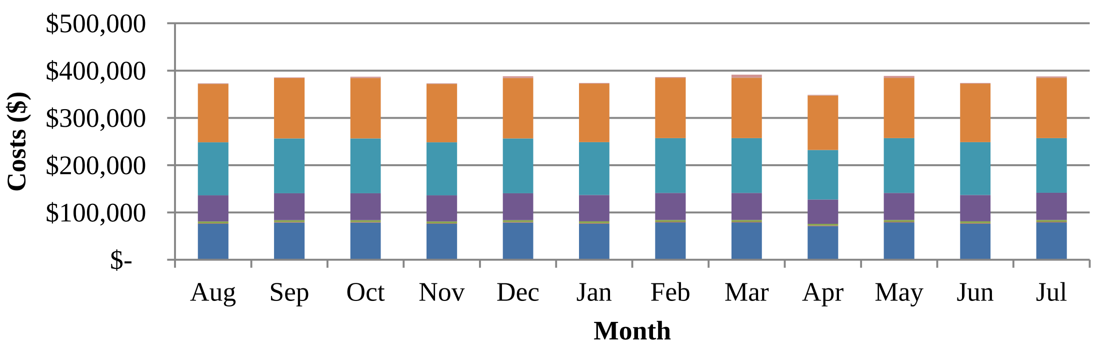


Figure 7-5: Fermentation biorefinery supply chain monthly production profitability ($/gallon)

To properly explain the reason for the phenomena presented above, the monthly costs for the 0.5 million gallon, 1.89 million gallon, and 5.0 million gallon capacities plants are shown below in Fig. 7-6a, Fig. 7-6b, and Fig. 7-6c, respectively.



(a)



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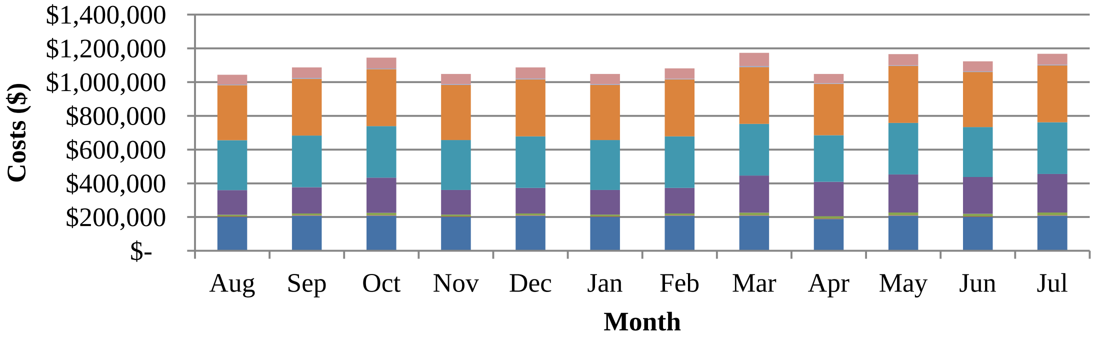

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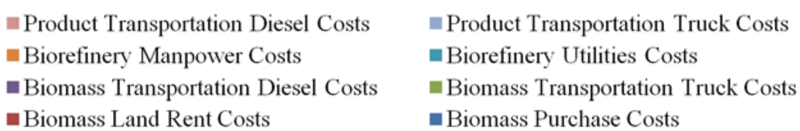
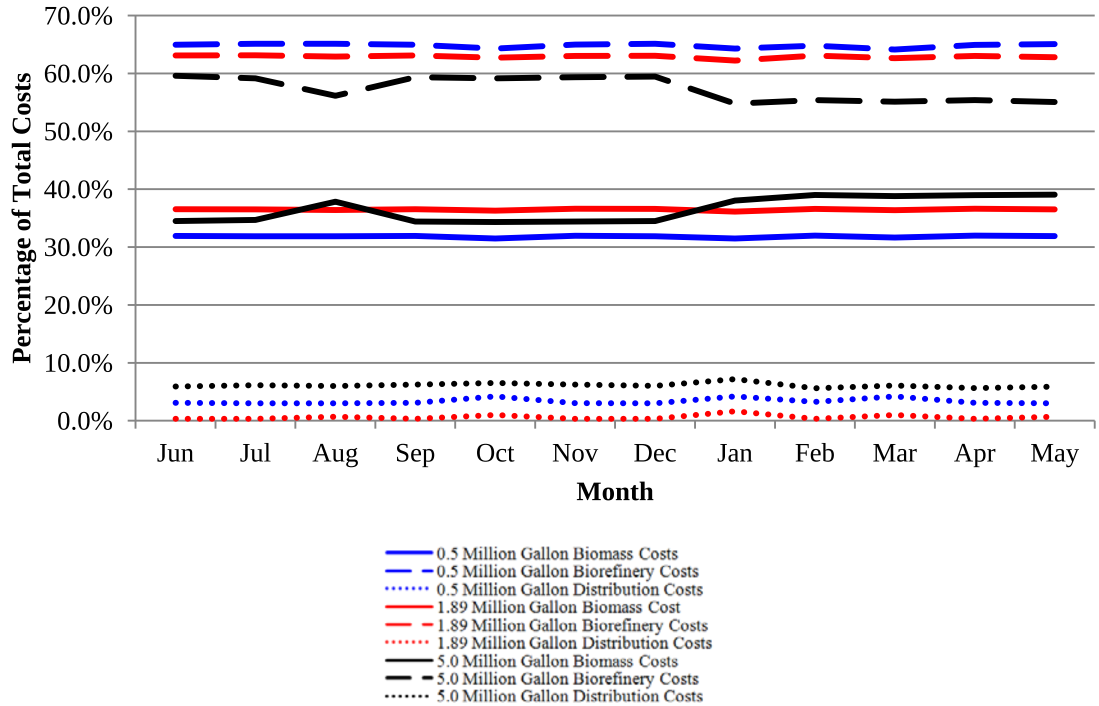


7-6: Monthly biorefinery costs ($/month), (a) 0.5 million gallon, (b) 1.89 million gallon, (c) 5.0 million gallon

A summary of the biomass, biorefinery, and distribution costs is provided in Fig. 7-7 below. The biomass costs include the purchasing of the biomass, land rent for storage at the feedstock location, truck transportation costs, and truck diesel costs. The biorefinery costs include the utility costs, labor, supervision, maintenance, and overhead costs at the biorefinery. Costs associated with the distribution costs include the truck transportation and diesel costs to transport the ethanol to the market distribution locations. For each plant size, the biomass cost as a percentage of total costs increase throughout the year. This is due to the biorefinery being supplied by the nearest feedstock location first to take advantage of all the biomass before it degrades. Then it is supplied by locations farther and farther away to meet the monthly production requirements as biomass is either used or degrades at each feedstock location. Even though the biorefinery costs makeup a large portion of the total overall costs, the operating costs are linearly proportional to the capacity of the plant. The costs associated with distributing the ethanol to the market for the 5.0 million gallon plant is greatest as it supplies 5 counties over the course of the year, whereas the other two plant sizes only serve 2 counties throughout the year. However, 1.89 million gallon plant (located in Calloway County) has a smaller distribution costs as a percentage of total costs when compared to the 0.5 million gallon plant. This is due to both plants supplying 2 different counties and Fulton County (where the 0.5 million gallon plant is located) having a smaller monthly ethanol demand. Therefore, to obey the constraints, ethanol is needed to be transported to another county for consumption, consequently driving up product transportation cost.



7-7: Monthly costs as a percentage of total monthly costs (%)

7.2 Fermentation Additional Decisions

Compared to the integrated biorefinery scenario, additional decisions are only needed to make the 5.0 million gallon plant supply chain configuration profitable as the 0.5 million gallons and 1.89 million gallons plants and their respective supply chains are profitable throughout the year as well as steadily profitable every month. Since the biomass costs ranges from approximately 30-40% of the total supply chain costs, as with the integrated biorefinery scenario, a subsidy of $7 per ton paid directly to the farmer was analyzed resulting in increased monthly profitability for each plant size as shown in Fig. 7-8 below. The 5.0 million gallon plant is profitable for 5 months out of the year but still does not turn a profit over a given year.

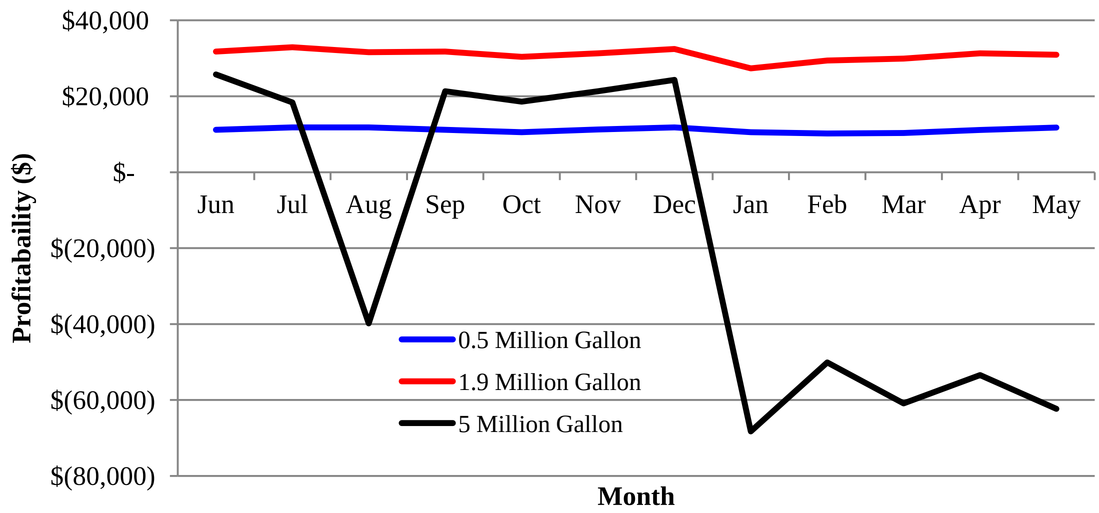


Figure 7-8: Monthly profitability with government subsidy to farmer ($/month)

Government subsidies are out of the biorefinery's operational control, therefore, the focus for the fermentation case study will be on potential market conditions and their ramification on the supply chain performance is conducted through a sensitivity analysis.

7.3 Fermentation Sensitivity Analysis

The results of this analysis, just as in chapter 6, are obvious because one can clearly say that product price increases will increase profitability. Given the total annual profitability for each plant size, a sensitivity analysis was conducted ranging the price of ethanol and diesel as shown in Fig. 7-9 and Fig. 7-10, respectively. The price ranges analyzed are $1.50-$3.25 per gallon of ethanol and $3.00-$4.75 per gallon of diesel. Note that the price of ethanol is based on wholesale ethanol, not the typical E85 (85% ethanol, 15% gasoline) as seen at the pump.

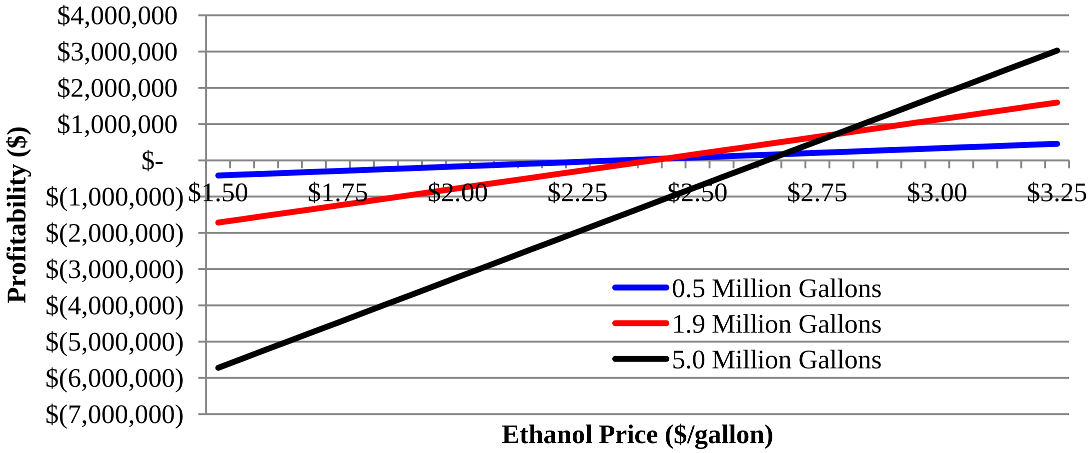


Figure 7-9: Annual profitability with ranging ethanol price ($/year)

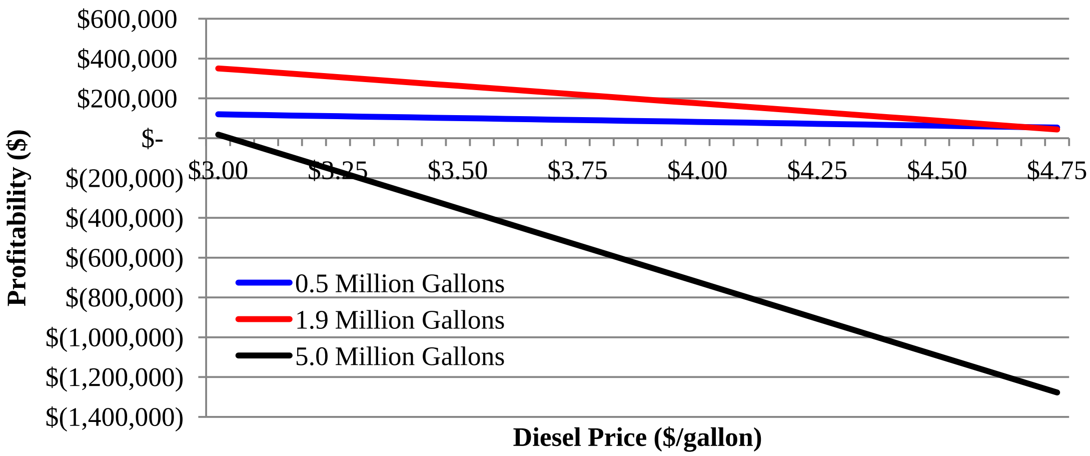


Figure 7-10: Annual profitability with ranging diesel price ($/year)

From the sensitivity analysis, it is apparent the price of ethanol has the largest impact on supply chain profitability for each supply chain configuration. An increase of $0.15 per gallon from the $2.50 per gallon price turns an annual profit for all plant sizes including the 5.0 million gallon plant. A price above $2.80 per gallon makes the 5.0 million gallon plant the most profitable of the three plant sizes. However, a drop in ethanol price has severe impact on the 5.0 million gallon plant, whereas the impact is less for the 0.5 million plant and the 1.89 million gallon plant. While holding other costs and prices constant, the 0.5 million gallon supply chain and 1.89 million gallon supply chain were still profitable over the year given a diesel price range of $3.00-$4.75 per gallon. On the other hand, the 5.0 million gallon plant and respective supply chain was only profitable with a diesel price of $3.00 per gallon. From these observations, the price of ethanol is concluded to have the largest supply chain ramifications, while the price of diesel has little ramifications on supply chain profitability for the fermentation scenario.

From the results and observations presented in the past two chapters given the case study in the Jackson Purchase Region of Western Kentucky, conclusions made from the model and methodology presented in Chapter 3 as well as the path forward will be discussed in more detail in the following chapter.

8 CONCLUSIONS & FUTURE WORK

This research presented a methodology and a region specific tool which included strategic and tactical level decisions into the design of a biorefinery supply chain to aid in the decision making process for policy makers and potential investors. Using the Jackson Purchase Region in Western Kentucky as a case study, two conversion technologies were analyzed and compared for the production energy, fuels, and chemicals from local lignocellulosic biomass resources. Three biorefinery capacities were examined for each conversion technology. A MILP optimization model was built to determine the location of each plant and its respective supply chain configuration as well as the monthly allocation of each biomass feedstock and product by maximizing profit over a one year time frame. Model constraints included monthly biomass feedstock availability at each feedstock location, monthly product demand at each market distribution location, the amount of feedstock and product transported in one truckload, and the amount of biomass required or the amount of product produced at the biorefinery. A method for improving supply chain performance post-optimality via strategic level decisions and government subsidies were also discussed to provide a more extensive analysis.

Current research lacks models which consider the monthly availability of second-generation biomass feedstock and local monthly product demand. Therefore, this research attempts in bridging this gap by evaluating corn stover, forest residue, and poultry litter for the production of gasoline, diesel, natural gas, electricity, and residual fuel oil using a integrated biorefinery approach via gasification and Fischer-Tropsch synthesis. This was then compared against utilizing corn stover and winter wheat straw for the production of ethanol using a more conventional conversion technology via Saccharification and fermentation. A comprehensive literature review was then conducted for costs parameters inputs. If literature did not exist regarding operational costs and/or product conversion efficiencies, an ASPEN Plus model was built finding utility costs and product output via heat integration. The optimal supply chain configuration and monthly allocation of feedstocks and products were determined by the MILP optimization model which seemed to be a viable approach as each solution took approximately 11 and 85 seconds to solve for the fermentation and integrated biorefinery modeling scenarios, respectively, in ILOG OPL (ran on a personal laptop with an Intel Centrino processor with a clock speed of 2.00 GHz).

From the three capacities studied for each conversion technology, the two smaller fermentation biorefinery capacities and respective supply chain configurations performed the best overall given the case study. Even though these two biorefinery supply chain configurations were not as sensitive to the price of diesel as the others were. The price of ethanol had a large impact on the supply chain performance due to being the only source of revenue. For this reason, the integrated biorefinery has a processing advantage given the right market conditions and proper biomass feedstock mix. The integrated biorefinery scenario heavily depended on the availability of corn stover due to having the same required amount from September through July. Therefore, investigating a feedstock portfolio which depended less on the amount of corn stover may have an economical advantage to what was studied. The costs associated with purchasing and transporting the biomass to the biorefinery seemed to be greatest as a percentage of total supply chain costs for the integrated biorefining scenario. On the other hand, the costs of processing the biomass into the desired products were greatest for the fermentation scenario as a percentage of total supply chain costs. Therefore, given the processing expertise in Kentucky for producing ethanol for the sale of alcohol (especially bourbon from corn grain), the fermentation conversion technology may be advantageous for Kentucky so that production and supply chain upsets are avoided through operational experience knowledge and experience with corn availability and price, respectively.

However, a limitation with the integrated biorefinery scenario was that the profit was not able to be maximized through the process simulation due to the Economic Optimization feature only being able to handle two of the three physical states (liquids and gases, not solids). Consequently, since biomass is in the solid state, a decision variable representing the amount of biomass required at the biorefinery could not be defined while optimizing biorefinery utility cost within the process simulation model. Thus, future studies investigating the other biomass feedstock mix ratios may have more favorable supply chain results than the ones studied for the integrated biorefinery scenario.

As the demand for energy, fuels, and chemicals derived from cellulosic resources due to governmental mandates is set to increase in the upcoming years, total supply chain costs from field-to-market, must be similar to those of fossil fuels for consumers to participate. Further improvements in the model could include a different mode of transportation of biomass and products as the most expensive mode, truck transport, was evaluated with this study. A more efficient densification system, either mechanical into pellets or chips or chemical via Pyrolysis could be evaluated using this tool so that more biomass could be transported at once, thus driving down transportation costs and overall supply chain costs.

Neither Renewable Energy Certificates (RECs) for the production of electricity or Renewable Identification Numbers (RINs) for the production of renewable gasoline, diesel, and ethanol were used as a revenue source in this study. An increase in profitability, thus supply chain performance for all plant capacities in each modeling scenario would be seen if government subsidies were considered such as REC's and RIN's. On the other hand, government subsidies paid directly to the farmer instead of the energy producer has the potential of alleviating supply chain costs related to biomass purchasing costs but also can be done at a cheaper rate on a per gallon or energy output rate than what is currently in place all while incentivizing the supplier (farmers or aggregators). Therefore, more biomass would become available and thus driving down supply chain costs even further. Given that only one example was studied, future studies involving government subsidies in a more detailed manner could also provide further insight to policy makers.

The optimal supply chain configuration found for each scenario in this research could also depend on other parameters and/or constraints that were not considered on a broader scale. For example, capital costs to build the biorefinery could have a large impact on the supply chain performance as the payback period to repay the initial capital to build the biorefinery was not considered. If capital costs were included, the resulting size of the biorefinery and respective supply chain configuration would be heavily dependent on the capital cost input. Capital costs vary drastically year-to-year given the global raw material demand (steel in this case for the equipment), equipment vendor shop floor backlog, local labor availability, credit availability, and interest rates. For these reasons, the impact of capital costs on supply chain performance should be done post-optimality so that a more extensive analysis can be conducted through multiple market scenarios. Environmental impacts and/or constraints such as greenhouse gas (GHG) emissions throughout the supply chain and the impact of potential large amounts of water diverted from local streams and rivers to be used at the biorefinery were also not considered in this study. Given multiple supply chain configurations, a total life-cycle analysis (LCA) could be conducted to select the most environmentally friendly supply chain configuration.

Given the capability to interface with various process simulations, this region specific tool provides the capability for policy makers and potential investors to evaluate multiple feedstock-to-product pathways. The approach developed in this research provides to be a platform for further integration with other modeling tools. The availability of potential biomass feedstocks depend on a number of factors such as rainfall, growing degree days, and crop infestation just to name a few. The demand for the created products also depend on a wide variety of factors such as price, unemployment rate (the higher the rate, the less amount of people have jobs, the less money the general public has to spend), and the regions infrastructure capacity. To properly capture the variation in biomass availability and product demand, a modeling tool such as discrete-event simulation (DES) will help in the decision making process as the tool will evaluate the robustness of a given supply chain over a longer period of time given the randomness of such activities. From the relationships found between the parameters and different variables found from the use of this tool as well as the discrete-event simulation model, further evaluation and analysis can then be conducted via systems dynamic modeling to provide a more holistic analysis to policy makers and potential investors.

Incorporating strategic and tactical level decisions in the supply chain design of a biorefinery is not only a more realistic approach but the resulting supply chain will be more resilient to varying market conditions. Alas, the resulting supply chain configuration should further reduce the dependency on foreign crude oil from unstable areas for the production of energy, fuels, and chemicals as well as reducing the greenhouse gas emissions related to our energy supply all while involving local rural economies.

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<u>Publications</u>

Faulkner, W. and Badurdeen, F. (2012) “Sustainable Value Stream Mapping (Sus-VSM): Methodology to Visualize and Assess Manufacturing Sustainability Performance”, *Journal of Cleaner Production*. Submitted for Review.

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