

2014

Modeling and Optimization of Woody Biomass Harvest and Logistics in the Northeastern United States

Damon S. Hartley

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**Modeling and Optimization of Woody Biomass Harvest and
Logistics in the Northeastern United States**

Damon S. Hartley

Dissertation submitted

**to the Davis College of Agriculture, Natural Resources and Design
at West Virginia University**

in partial fulfillment of the requirements for the degree of

**Doctor of Philosophy in
Forest Resources Science**

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Division of Forestry and Natural Resources

Morgantown, West Virginia

2014

Keywords: SRWC, Simulation, Suitability, Storage, Preprocessing, MILP

ABSTRACT

Modeling and Optimization of Woody Biomass Harvest and Logistics in the Northeastern United States

Damon S. Hartley

World energy consumption is at an all-time high and is projected to continue growing for the foreseeable future. Currently, much of the energy that is produced comes from non-renewable fossil energy sources, which includes the burden of increased greenhouse gas emissions and the fear of energy insecurity. Woody biomass is being considered as a material that can be utilized to reduce the burden caused by fossil energy. While the technical capability to convert woody biomass to energy has been known for a long period of time, the cost of the feedstock has been considered too costly to be implemented in a large commercial scale. Increasing the use of woody biomass as an energy source requires that the supply chains are setup in a way that minimizes cost, the locational factors that lead to development are understood, the facilities are located in the most favorable locations and local resource assessments can be made.

A mixed integer linear programming model to efficiently configure woody biomass supply chain configurations and optimize the harvest, extraction, transport, storage and preprocessing of the woody biomass resources to provide the lowest possible delivered price. The characteristics of woody biomass, such as spatial distribution and low bulk density, tend to make collection and transport difficult as compared to traditional energy sources. These factors, as well as others, have an adverse effect on the cost of the feedstock. The average delivered cost was found to be between \$64.69-98.31 dry Mg for an annual demand of 180,000 dry Mg. The effect of resource availability and required demand was examined to determine the impact that each would have on the total cost.

The use of woody biomass for energy has been suggested as a way to improve rural economies through job creation, reduction of energy costs and regional development. This study examined existing wood using bio-energy facilities in the northeastern United States to define the drivers of establishment of bio-energy projects. Using a spatial econometric framework, a spatial autoregressive probit model was estimated based on the Bayesian methods to define the factors that impact the location of wood using bio-energy facilities in the United States. Through the analysis it was found that the energy policy of the state is the biggest driver of the choice of location for bioenergy facilities.

The choice of site is of great importance when trying to meet the goal of producing cost-effective biofuels, due to the spatial dispersion of the biofuels and the high proportion of total cost that is incurred by transportation to the processing facility. The proximity to the fuel supply and the resulting transportation cost are the primary concern of the operators of the facilities, although this is not the primary driver that leads to the development of these projects. In order to make these endeavors successful, there must also be buy-in from the local community and its government. Previous studies have found that in addition to the environmental benefits and improved energy security, the impact that the facilities have on the local economy, in terms of job creation, improved industrial competitiveness and regional development are key drivers of bioenergy projects. A two-stage site selection approach is developed for the siting of woody biomass facilities, which combines multi-criteria analysis with mixed integer linear programming to rank potential development sites. This approach was then applied to the siting of a Coal/Biomass to liquids plant, and was able to objectively identify the optimal location of the facility.

Finally, a simulation model was developed to assess the locally available quantities and prices for biomass feedstocks. The simulation uses machine tractability in conjunction with graph theory to assess machine productivity and harvesting cost. The model was then applied to a demonstration project in which a 10,000 bbl per day Coal/Biomass to Liquid plant is being used to examine if there are sufficient feedstocks available to warrant the project. It was found that within the proposed three county procurement area that there were approximately 34% less material available than was assumed to be available from large scale feedstock data. Also, the simulation model was able to determine that the total feedstock requirement could be met at a price of \$66 per dry Mg.

Acknowledgements

I would first like to thank my major professor Dr. Jingxin Wang for providing me with this opportunity and the guidance that he provided throughout my time at West Virginia University. He provided me with numerous opportunities to grow professionally and helped keep me heading in the right direction as I navigated the course of study. I would also like to thank my committee members: Dr. Daniel Robison, Dr. Joseph McNeel, Dr. Michael Strager, Dr. Debansu Bhattacharyya, Dr. J. Wesley Burnett and Dr. Erin Searcy for their donation of time and the valuable comments and advice.

Additionally, I would like to thank my family for the support that they have given. Especially, my loving wife, Leslie, who provided endless encouragement and reassurance during the last four years. Also, my sons: Nick and Alex, who were always there to lighten my mood, and to provide motivation needed to continue.

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1 INTRODUCTION

World energy consumption is at an all-time high and is projected to continue growing for the foreseeable future. According to 2010 projections from the Energy Information Administration (EIA), world-wide energy consumption is expected to increase from 522.25 PJ (495 quadrillion BTU's) in 2007 to 779.69 PJ (739 quadrillion BTU's) in 2035, which is an increase of 49% (EIA, 2010). This projected increase is mostly attributed to increased energy demand in China and India. Energy consumption in these areas is projected to increase more than 110% over the next 25 years. While in North America and Europe the demand for energy is projected to increase by 9.6% over the same time period (EIA, 2010).

The United States and the European Union consumed over 188.85 PJ (176 quadrillion BTU's) of energy in 2008. In the United States approximately 40% of the demand is from the electric power sector. The production of electricity in the United States is dominated by fossil fuels, which account for more than two thirds of all electricity produced. In the European Union the story is similar, about 40% of all energy consumed is in the form of electricity and over half of the production comes from fossil fuels (EIA, 2010).

The burning of fossil fuels contributes to an increase in the atmospheric concentrations of greenhouse gasses which has been linked to global climate change. Additionally, political instability in fuel rich countries has led to increased energy security concerns by countries dependent on imported fuel sources. For this reason many countries are searching for renewable and sustainable alternatives to conventional fossil fuel production.

Renewable energy sources, such as solar, wind and biomass are being considered for use as a feedstock for large scale energy production, but each type has limitations on the locations where they would be effective. In the northeastern region of the United States, the prospect of using solar or wind for energy generation might not be very promising due to geographical and weather related factors. A study by the National Renewable Energy Laboratory (National Renewable Energy Laboratory, 2010) found that only 14.86% of the land area in the northeast region was suitable for harvesting wind energy at a 30% gross capacity level. Similarly, climate data from the Northeast Regional Climate Center found that, on average there are only 80.27 clear days per year and nearly 50% of the days have 80% or more cloud cover.

In areas where solar and wind energy generation might not be very suitable, the use of biomass may be a feasible solution. This is especially true for the areas covered by temperate forests. Wood has been shown to produce much lower levels of air pollution than coal. This is because the sulfur and nitrogen content of wood is low which produces negligible amounts of SO_x and NO_x emissions. In addition the combustion of wood also produces much less CO₂ than the combustion of coal (McIlveen-Wright et al., 2001). Also, the use of biomass also promotes a more secure energy environment as having multiple fuel sources increases the power grids ability to respond to resource supply disruptions (Brown and Mann, 2008). Forest derived biomass, which has historically produced more than 14% of the world's energy, is one of the largest and most sustainable energy resources. Woody biomass, which includes residues from timber harvest, residues from primary and secondary wood processing and tree removals during fuels reduction and pre-commercial thinning, residues from surface mining and shale gas drilling, and short rotation woody crops, has the potential to be a feedstock for both liquid fuels

and the production of electricity (Kaylen et al., 2000; Bridgwater et al., 2002; Tembo et al., 2003; Thek and Obernberger, 2004; Caputo et al., 2005, Wang et al., 2006).

The potential worldwide woody biomass supply is estimated to be able to produce 150 EJ/yr or 1.43 times the annual energy consumption of the United States (Faaij and Domac, 2006). In the United States, temperate forests are located in the eastern and northwestern portions of the country, and are estimated to be able to produce approximately 51.71 million dry tonnes (57 million dry tons) of biomass at a price of \$66.14 per dry tonne (\$60 per dry ton) (Perlack et al., 2011). That is enough material to produce approximately 88 billion kWh or 12.87 billion liters (3.4 billion gallons) of liquid fuel, based on 15.18 GJ per tonne (16 million Btu per ton) and 33% efficiency for electricity and 227.12 liters (60 gallons) per dry ton (American Physical Society, 2013; Perlack et al., 2011).

Traditionally, woody biomass has been considered a low value product, because of this little emphasis has been placed on the efficient harvest, extraction and transport. As energy markets develop, value will be added to these products, which will lead to increased harvest and collection (Becker et al., 2009). Even with the increases in market value associated with increased demand, harvesting and collection costs may be a limiting factor in the true availability of woody biomass feedstock. While collection and primary transport of logging residues can be completed using current timber harvesting systems, their efficiency is dependent on machine payloads, the terrain in which they are working and the spatial distribution of the residue. Short rotation woody crops (SRWC) provide similar challenges, currently available technology is not mature enough to meet efficiency goals, and similarly to forest residues the spacing of SRWC planting causes transportation challenges. Each one of these factors will affect the cost of the

feedstock production. In addition, transportation of woody biomass is also a challenge due to the material's low bulk density, which makes it hard to maximize allowable load limits (Spinelli et al., 2007).

Therefore, this project will specifically optimize biomass feedstock logistics with considerations of maximizing positive economic impact and minimizing environmental impact. This will be accomplished through: (1) Analysis and optimization of woody biomass harvest and logistics in the northeastern United States. (2) Assessments of the regional drivers for bioenergy development using econometric techniques. (3) Analysis of biomass business development using multi-criteria optimization of environmental and economic impacts. (4) Economic modeling of woody biomass utilization for bioenergy under constraints of terrain, machine capability and harvest.

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2 OPTIMIZATION OF WOODY BIOMASS SUPPLY CHAINS IN THE NORTHEASTERN UNITED STATES

Abstract

Biomass derived from forests and short rotation woody crops (SRWC), could hold the key for renewable energy production in the Northeastern United States. While woody biomass is a potential feedstock for a diverse set of energy development options, little emphasis has been placed on developing supply chains to efficiently deliver the resource to the end user in this region. This study developed a mixed integer linear programming model to efficiently configure woody biomass supply chain configurations and optimize the harvest, extraction, transport, storage and preprocessing of the woody biomass resources to provide the lowest possible delivered price. The characteristics of woody biomass, such as spatial distribution and low bulk density, tend to make collection and transport difficult as compared to traditional energy sources. These factors, as well as others, have an adverse effect on the cost of the feedstock. The average delivered cost was found to be between \$64.69-98.31 for the base scenario. The effect of resource availability and required demand was examined to determine the impact that each would have on the total cost. Through analysis the optimal location of facilities and their respective capacities were determined along with the configuration of the supply chain that is used to deliver feedstocks to the facilities.

2.1 INTRODUCTION

Currently in the northeast United States, as well as the rest of the country, a majority of energy consumption is based on fossil fuels. The burning of fossil fuels has been shown to have negative environmental impacts, and in the case of petroleum, the largest used fossil fuel, the majority is imported; threatening the national energy's independence and diversity. Biomass, on

the other hand, has been shown to have less environmental impact and can be produced domestically, reducing security concerns and enhancing local, rural economies. While environmental benefits and domestic energy security are touted during the development of bioenergy projects, the real drivers are the potential for job creation, improved industrial competitiveness and regional development (Domac et al., 2005).

Biomass for bioproducts and bioenergy can be sourced from forests, agricultural crops, various residue streams, and dedicated woody or herbaceous crops. Woody biomass feedstocks have several advantages over agricultural sources, especially in the northeastern US (NE) where forests make up 67.4% of the total land area (Smith et al., 2009) and agricultural production has been in a 20-year decline. Woody biomass is available year-round from multiple sources, so end users are not dependent on a single source of material; this ensures a consistent feedstock supply, reduces the risk of dramatic price fluctuations, and eliminates the needs for complicated and expensive long-term storage of material. As perennial cropping systems, both forests and short rotation woody crops (SRWC), like willow and hybrid poplar, produce a number of environmental benefits beyond a renewable source of biomass and are relatively less prone to fluctuations in yield due to abnormal weather patterns or pest and disease outbreaks than annual crops.

The Northeast already has a wealth of existing feedstocks and the potential to increase supplies in the future. There are currently between 1.35 and 25.64 million dry tons of woody biomass available per year in the northeast at a price between 60 and 90 per dry ton (a citation). It is also estimated that the region will be able to sustainably produce between 80.7 and 141.5 million dry tons of biomass per year, in the form of Short Rotation Woody Crops and energy

grasses, by the year 2030 (Perlack et al., 2011) . The availability of these resources provide a competitive advantage for economic development (Marcouiller et al., 2004). Biomass harvesting, transportation and processing are labor intensive, and the spatial distribution and relatively low bulk density limit the economical transportation distance of these materials; leading to markets that are distributed throughout a region.

In terms of energy production, the biomass supply chain possesses characteristics that make it markedly different from those of conventional energy sources (Rentizelas et al., 2009). Supply chains for bioenergy feedstocks have adopted their structure from the traditional industries from which they have been derived, i.e. agriculture and forest products (Kenney et al., 2013). The biomass supply chains are rigid and minimally adaptable to changes in the type of feedstocks. Additionally, there are challenges that are faced in bioenergy supply chains that are not faced by conventional energy. First is the temporal availability of the biomass. In the case of woody biomass, the availability is affected by seasonal weather patterns while dedicated energy crops and agricultural residue availability are primarily controlled by harvest timing (Abrahamson et al., 2010; Inman et al., 2010; Wu et al., 2011) . As a result, individual feedstock types may not be capable of producing quantities that are sufficient to ensure a continuous supply at a price demanded by industries. The second factor that differentiates the supply chains of woody or herbaceous biomass from those of conventional fuels is the spatial availability of the biomass. The wide dispersion pattern of individual biomass types results in increased transportation cost in order to meet production demands (Gonzalez et al., 2011). Finally, the energy density of biomass feedstocks are much lower than that of traditional energy feedstocks, approximately 40%-55% lower than coal or petroleum (McKendry, 2002), requiring a greater

quantity of feedstocks to equal the energy output that is being replaced. The result is a further increase in the cost of transporting the biomass materials (Caputo et al., 2005).

The method of harvesting used for woody biomass is dependent on the source of the biomass, i.e. forest grown biomass, residues or SRWC. For forest grown biomass, the most common method is to harvest biomass in conjunction with commercial timber harvest. As a result the majority of the harvesting of forest grown biomass is accomplished with conventional logging equipment, while SRWC is generally harvested with a cut and chip type machine; that uses a converted agricultural harvester as the base machine. Forest biomass is transported from the harvest site as either loose residue or chips. The transportation of loose residue is only a preferred method of transport when the hauling distances are short, since vehicle payloads are rarely fully utilized, in terms of weight (Spinelli et al., 2007) . The process of chipping or grinding woody material, or even bundling of loose residues is generally preferable, as the process can improve bulk density, homogeneity, and handling characteristics of the raw material from the forest (Hartsough et al., 1997; Jeuck and Duncan, 2009; Johansson et al., 2006).

The issues faced by bioenergy feedstock supply chains; such as temporal availability, insufficient local supply, variability of material and low bulk and energy densities, could be mitigated by the use of mixed feedstocks, biomass material size reduction and densification or other management practices. Supply chains that are comprised of both woody and herbaceous materials including dedicated energy crops (i.e. Shrub Willow, Switchgrass, Miscanthus), agricultural and forest residues. Thermally pretreating the materials will homogenize the different materials, creating a material that is uniform and more energy dense than the original raw feedstocks (Ciolkosz and Wallace, 2011; Lehtikangas and Skogshushållning, 1999) further

pretreatment by densification will further improve the transportation properties (Ciolkosz and Wallace, 2011). In areas where multiple feedstocks exist, and quantities are not sufficient to completely meet demand; it is reasonable to expect that the supply chains will become mixed. The added benefit would be that as technology advances, the mixing of feed- stocks may enhance yields and improve the overall feedstock characteristics (Shi et al., 2013). Through mixing and formulation, consistent supplies will be able to be delivered to meet the tonnage demands of the bioenergy facilities (Shi et al., 2013), while simultaneously minimizing the procurement radius.

The optimization of biomass supply chains has been examined from a variety of perspectives, but essentially there has been two main goals: maintaining competitive prices and ensuring a continuous supply (Gold and Seuring, 2011). DeMol et al. (1997) used optimization to determine the lowest cost network structure and resulting biomass flows of a multi-source (tree prunings, wood waste, waste paper, and forest thinnings) woody biomass system in the Netherlands. The models were solved by first solving sub-models for each feedstock source and then combining the results into a knapsack model to find the optimal set of facility locations and transportation routes. Troncoso and Garrido (2005) used a mixed-integer linear programming (MILP) formulation to simultaneously solve a combined production, facility location and freight distribution problem to minimize transportation costs and ensuring demand is met for the forest products industry in Chile. This methodology could readily be adapted to the bio-energy sector, but may be limited to the size of problems that can feasibly be solved. Ravula et al. (2008) used cotton logistics in Virginia as an analog for biomass transport and optimized the logistics system via the use of greedy algorithms and an implementation of the knapsack problem with travel

times. Wu et al.(2012, 2011, 2010) used a MILP approach to estimate the optimal delivered cost of harvesting and mill residues for the production of liquid fuels in the Central Appalachian region of the United States. These models aggregated the supply to a central location within a county, which simplified the formulation of the answer but aliased the true transportation costs from the field to the conversion facility.

The utilization of biomass as an energy feedstock in the northeastern United States can potentially provide a means toward energy security and independence, while simultaneously creating environmental and economic benefits for the region. Biomass has been shown to have less environmental impact and can be produced domestically, reducing security concerns and enhancing local, rural economies. However, the current methods and logistics used to harvest and transport renewable energy feedstocks are unable to deliver these feedstocks at a price, at which they can compete with traditional fossil fuels for energy production. If the large scale adoption of biomass as an energy feedstock is to occur in the region, methods of harvest and logistics must be employed that minimize costs while maintaining the environmental benefits.

2.2 MODEL DEVELOPMENT

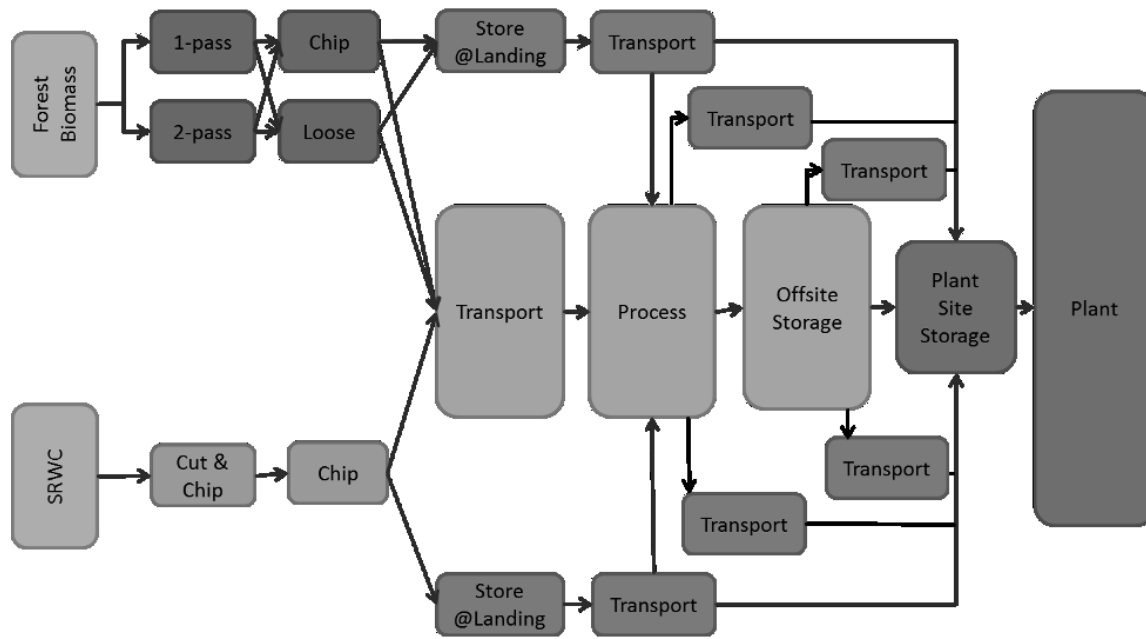


Figure 2-1 Graphic representation of proposed woody biomass supply chains.

In terms of energy production, the biomass supply chain possesses characteristics that make it markedly different from those of conventional energy sources (Rentizelas et al., 2009). Supply chains for bioenergy feedstocks have adopted their structure from the traditional industries from which they have been derived, i.e. agriculture and forest products (Kenney et al., 2013). The biomass supply chains should be rigid and minimally adaptable to changes in the type of feedstocks. Additionally, there are challenges that are faced in bioenergy supply chains that are not faced by conventional energy. First is the temporal availability of the biomass. In the case of woody biomass, the availability is affected by seasonal weather patterns while dedicated energy crops and agricultural residue availability are primarily controlled by harvest timing (Abrahamson et al., 2010; Inman et al., 2010; Wu et al., 2011). As a result, individual feedstock types may not be capable of producing quantities that are sufficient to ensure a continuous

supply at a price demanded by industries. The second factor that differentiates the supply chains of woody or herbaceous biomass from those of conventional fuels is the spatial availability of the biomass. The wide dispersion pattern of individual biomass types results in increased transportation cost in order to meet production demands (Gonzalez et al., 2011). Finally, the energy density of biomass feedstocks are much lower than that of traditional energy feedstocks, approximately 40%-55% lower than coal or petroleum (McKendry, 2002), requiring a greater quantity of feedstocks to equal the energy output that is being replaced. The result is a further increase in the cost of transporting the material (Caputo et al., 2005). The potential supply chain that is being proposed (figure 1), integrates the harvesting of forest and SRWC biomass into a single supply chain. In addition, processes for improving the transportation properties are considered (i.e. centralized chipping and pelletization) along with storage to ensure that consistent supplies are available at all time periods.

A MILP model was formulated to maximize the economic profit of delivering woody biomass feedstocks to the gate of a conversion facility. The optimal levels for the decision variables include quantity of feedstock harvested and the quantity of feedstock transported between harvest, processing, storage and conversion for each time period of the year, the location of storage, processing and conversion facilities. An explanation of the objective function and the constraints of the proposed model are given in the following sections.

2.2.1 Objective function

The objective of the proposed model is the maximization of economic profit (ψ) that is realized by the production of woody biomass energy feedstocks. Total profit takes into account the revenue(φ) that is earned by delivery of a feedstock to the gate of a bioenergy facility; and

subtracts the costs that are associated with the harvest (η), processing (ρ), storage (μ) and transport (τ) of the feedstock. Equation 1 gives the formulation of the objective function.

$$Max\psi = \phi - \eta - \rho - \mu - \tau$$

The revenue is calculated through the use of the following equation:

$$\phi = \sum^M \sum^T \left[\left(\sum^I \sum^J xhc_{mijt} + \sum^J \sum^K (xpc_{mjkt} + xsc_{mkjt}) \right) * mprice_m \right] \quad (2-2)$$

where xhc_{mijt} represents the quantity of material m that is shipped to the biomass facility j from the harvest site i during time period t , xpc_{mjkt} is the quantity of material m that is shipped to the biomass facility j from processing facilities k during time period t and xsc_{mkjt} is the quantity of material that is shipped to the biomass facilities j from storage k during time period t . The total volume is then multiplied by the material selling price denoted by $mprice_m$.

In addition to the revenue, cost must also be considered. The cost of harvesting the biomass feedstock is primarily made up of two parts: the cost of the actual harvesting operations and payment to the landowner. The cost of the harvesting operations is made up of fixed and variable cost of the machinery and operators; including taxes, insurance and fringe benefits. Additionally, there is also an expense of paying the landowner for the right to harvest their material and to pay for the expenses that were incurred during the establishment and growing of the feedstock. In this model three harvest methods were considered: Extracting forest material with a grapple skidder and shipping the material in loose form to a centralized chipping facility,

extracting forest material with a grapple skidder and chipping on site, and harvesting SRWC with a single pass cut and chip machine. This model also makes the assumption that all feedstocks are accumulated at the centroid of the source county, to ensure that costs were not underestimated an aggregation cost was added to each of the feedstocks. The total harvesting cost was calculated using the following equation:

$$\eta = \sum^T \sum^P \sum^I [zh_{pit} * (hc_p + itc_{ip})] \quad (2-3)$$

With itc_{ip} being calculated by the following equation:

$$itc_{ip} = 2/3 \sqrt{\frac{Area_i}{\pi}} \times wf \times tr_p \quad (2-4)$$

where $Area_i$ is the area of the source county i . wf is a winding factor and tr_p is the transportation cost $\$on^{-1}mile^{-1}$ for the materials produced by process p .

The model also considers the cost of processing before delivery to the gate of the bioenergy facility. Through preprocessing the material it is possible to improve these characteristics and gain efficiency through the chain by reducing the material size, increasing the bulk density and/or increasing the energy density. Size reduction of the material from whole stems or large sections into chips is one of the most common processing methods to improve transportation properties. Chipping alone increases the bulk density of woody biomass by 243 percent, and the larger surface area allows for more transporational drying and improving the energy characteristics; on the down side the material is more sensitive to precipitation (Angus-Hankin et al., 1995; T. L. Richard, 2010). In addition to size reduction, pre-processing through

densification can also improve the logistical properties of woody biomass. Biomass can be densified at the harvest site through the use of baling or bundling. Baling or bundling involves compressing a material and tightly binding the compressed material to maintain the compression, for woody biomass this process has the ability to double the bulk density over loose material (Angus-Hankin et al., 1995). Also, densification can take the form of pelleting or briquetting; in this process comminuted woody biomass is compressed under high pressure and increased temperature then extruded through a die to produce cylindrical com-pressed biomass. The increased temperature softens the lignin in the material, which then serves as a binder when it cools. Pelletizing and briquetting improves the energy density in addition to the bulk density resulting in a feedstock with improved properties transportation, storage, conversion and material handling (Uslu et al., 2008). The cost of preprocessing is calculated with the following equation:

$$\rho = \sum^T \sum^P \sum^J (z_{pjt} * P_{cost_p} + PF_{cost_p} * y_{pj}) \quad (2-5)$$

In which the volume of material processed during a period (z_{pjt}) is multiplied by the variable cost for the process (P_{cost_p}) and added to the fixed processing cost (PF_{cost_p}) associated with an opened facility (y_{pj}) located at a candidate location.

The ability to store woody biomass will be a key in ensuring that a sufficient supply is available throughout the year (Inman et al., 2010). The supply of woody biomass is affected by seasonality. The seasonal availability of feedstocks from SRWC is controlled by the timing of the harvest. The recommendation is for harvest to occur during the dormant seasons

(Abrahamson et al., 2010). Recommending a winter harvest will require that the chips are stockpiled for use during the remainder of the year. Logging residues are not limited to a specific season of harvest, but can be impacted by seasonal variations in the weather, with wet periods limiting the production capabilities of harvesting firms (Wu et al., 2011). This uncertainty in supply will also necessitate a certain level of storage to ensure sufficient supply during periods of reduced production. The cost of storage is included in the model and also includes the cost that arise from the loss of material during storage. The cost of storage is calculated with the following equation:

$$\mu = \sum^T \sum^P \sum^J [(z_{spjt} * sloss_p * slcost_p) + (sfcost_p * y_{spj})] \quad (2-6)$$

In which the volume of the material that is stored during using method p at location j during time period t is multiplied times the storage loss factor for storage method p and the variable storage cost for storage method p . This term is added to the fixed cost for storage method p which is multiplied by the binary variable that signifies if a storage facility that uses method p is open at location j .

Transportation of biomass is a major cost element in all energy projects and is of great importance in regards to bioenergy development and production, because of the relatively low energy density in comparison to fossil fuels (Saidur et al., 2011). It is estimated that 35% to 50% of the total cost of producing energy from biomass is made up of the delivered cost of the feedstock (Sultana and Kumar, 2011). The transportation of biomass feedstocks is affected by many factors including availability, demand and spatial distribution (Gonzalez et al., 2011).

With all these factors being equally considered, the transportation of woody biomass comes down to the properties of the feedstock itself. In particular, the factors of most concern are the bulk density, moisture content and heating value (Frombo et al., 2009). The bulk density of woody biomass varies from 140 kg/m³ to 340 kg/m³ depending on form, loose materials are the lowest and wood chips being the highest (Angus-Hankin et al., 1995). Transportation cost is calculated with the following equations:

$$\tau = \tau^h + \tau^s + \tau^p \quad (2-7)$$

where τ^h is the cost of transporting materials from the harvest locations, τ^s is the cost of transporting materials from storage and τ^p is the cost of transporting materials from processing facilities. The equations that are used to calculate each component are:

$$\tau^h = \sum^T \sum^M \sum^I \sum^J \left[(xhc_{mijt} + xhp_{mijt} + xhs_{mijt}) * dist_{ij} \right] * tc_m \quad (8)$$

$$\tau^s = \sum^T \sum^M \sum^J \sum^K \left[(xsp_{mjkt} + xsc_{mjkt}) * dist_{jk} \right] * tc_m \quad (9)$$

$$\tau^p = \sum^T \sum^M \sum^J \sum^K \left[(xpc_{mjkt} + xps_{mjkt}) * dist_{jk} \right] * tc_m \quad (10)$$

Where xhc_{mijt} , xhp_{mijt} and xhs_{mijt} are the volumes of material m that are shipped from harvest location i to the facility location j during period t for each type of facility conversion, processing and storage, respectively. The term $dist_{ij}$ is the distance in kilometers between harvest location i and facility location j . The term tc_m is the transportation cost for material m

2.2.2 Constraints

The objective function presented in the previous section is subject to a series of material balance, resource availability and operational constraints. The following equations represent the balance of materials flowing in and out of processes. Equations (11) and (12) consider the material balance for the harvesting operations. Equation (11) ensures that the amount of a material that is produced is less or equal to the available material plus material losses during harvesting; with a_{mp} being the material input coefficient for harvesting material m using process p , zh_{pit} being the quantity of material harvested using process p at harvest location i during time period t , and h_{mit} is the amount of available harvestable material m available at harvest location i during period t .

$$\sum_{p \in ph}^P (a_{mp} * zh_{pit}) + h_{mit} \geq 0 \quad m \in mhi \quad (2-11)$$

Equation (12) ensures that the amount of material that is transported from a harvest site is less than or equal to the material that is produced at the harvesting site.

$$\sum_{p \in ph}^P (a_{mp} * zh_{pit}) \Big|_{m \in mho} \geq \sum_{j=1}^J xhc_{mijt} \Big|_{m \in mhc} + \sum_{j=1}^J xhp_{mijt} \Big|_{m \in mhp} + \sum_{j=1}^J xhs_{mijt} \Big|_{m \in mhs} \quad (2-12)$$

The next two equations, equations (13) and (14) represent the material balance equations for processing. Equation 13 ensures that the quantity of material that is output from processing is

less than or equal to the material that is input plus any processing losses that are associated with the processing of material.

$$\sum_{p \in pp}^P (a_{mp} * z_{spjt}) + \sum_{i=1}^I x_{hp_{mijt}} + \sum_{k=1}^K x_{sp_{mjkt}} \geq 0 \quad m \in mpi \quad (2-13)$$

Equation (14) ensures that the amount of material that is shipped from a processing location is less than or equal to the quantity that is produced at that location.

$$\sum_{p \in pp}^P (a_{mp} * z_{spjt}) \geq \sum_{k=1}^K \left[x_{ps_{mjkt}} + x_{pc_{mjkt}} + x_{pp_{mjkt}} \right] \quad m \in mpo \quad (2-14)$$

The final material balance constraint, ensures that the storage level for a storage location equals the quantity of material that remains from the previous period plus the quantity that is shipped to the storage location during the current period.

$$\sum_{p \in ps}^P (a_{mp} * z_{spjt-1}) + \sum_{i=1}^I x_{hs_{mijt}} + \sum_{k=1}^K x_{ps_{mjkt}} = \sum_{p \in ps}^K z_{spjt} + \sum_{k=1}^K x_{sc_{mjkt}} + \sum_{k=1}^K x_{sp_{mjkt}} \quad m \in ms \quad (2-15)$$

The next section of constraints are classified as capacity constraints. Each location in the supply chain from harvest to conversion has an associated capacity. Harvest areas have a finite quantity of material that is available and the amount of harvestable material that is available is limited by the temporal availability factor. Wu et al. utilized a temporal availability factor to account for changes in accessibility of forest biomass throughout the year. Similarly, the harvest

of SRWC are carried out during the dormant period which allows for the use of a temporal availability factor. The capacity constraint on the harvest of materials is given in Equation (16), which limits the harvest during a period to the total available biomass for the location ($BAVAIL_{mi}$) multiplied by the temporal availability factor (TA_{mt}) for the material that is being harvested during a time period.

$$h_{mit} \leq BAVAIL_{mi} * TA_{mt} \quad (2-16)$$

For the processing portion of the supply chain there are two processing technologies that are being considered: centralized chipping and pelletization. Each of these processes require substantial capital investment and therefore if a facility is to be opened it is assumed that the capacity will be at least 75% utilized. Additionally each of the technologies has an upper limits on its productive capacities. The upper bound on processing is given by equation (17) and the lower bound is given by equation (18)

$$z_{Pp,j,t} \leq PCAP_p * y_{Ppj}$$

$$z_{Pp,j,t} \geq [PCAP_p * 0.75] * y_{Ppj}$$

where y_{Ppj} is a binary variable signifying if a processing method is opened at a candidate location.

The storage capacity constraint is similar to the processing upper bound, in that the largest quantity of material that can be stored at a location during a time period must be less than the storage capacity that is available at the location (equation (19)).

$$z_{s_{p,j,t}} \leq SCAP_p * y_{s_{pj}} \quad (2-19)$$

The quantities of each fuel type demanded are relative to the energy content of oven dried woody biomass (equation (20)).

$$z_{c_{m,c,j,t}} \leq SCAP_{m,c} * y_{s_{m,c,j}} \quad (2-20)$$

2.3 MODEL APPLICATION

2.3.1 Model Assumptions for Base Scenario

The model was applied to an area in the northeastern United States that is made up of New York, Pennsylvania and West Virginia. The Northeast already has a wealth of existing feedstocks and the potential to increase supplies in the future. In the northeastern US (NE) where forests make up 2/3 of the total land area (Smith et al., 2009). Additionally, the decline in rural economies has led to outmigration from rural communities to urban areas, weakening local economies. The production of bioenergy has been viewed as having the potential to contribute to rural revitalization, with products derived from multiple sources having a greater potential than shifting the use of current food crops (Rossi and Hinrichs, 2011). Bioenergy feedstocks can be used as the basis for manufacture of biomaterials, chemicals and energy. Multiple uses provide opportunities for diversification of the use of cellulosic feedstocks, by providing new opportunities along an extended supply chain for business development and market creation.

Table 2-1 Assumptions for the base Model.

Parameter	Values
Forest Availability	3.32 million dry Mg (3.68 million odt)
SRWC (10% of marginal land)	3.4 million dry Mg (3.78 million odt)
Harvesting Rate:	
Forest ^a	
Loose Residue	\$32.12/ dry Mg
In-wood Chipping	\$35.25/dry Mg
SRWC ^b	\$17/dry Mg
Stumpage/Growers payment	
Forest ^c	\$26.40/dry Mg
SRWC ^b	\$32.43/dry Mg
Intermediate Processing:	
Centralized Chipping ^d	Capacity(dry Mg/month):9450 Fixed Cost: 56,452/month Variable Cost: Variable Cost: 3.15 per dry Mg
Pelletization ^e	Capacity(dry Mg/month): 3750 Fixed Cost: \$27,400 per Month Variable Cost: 55.49 per dry Mg
Storage Methods ^{e,f}	
Chips:	
Open	Capacities (dry Mg):5132,10265,18249,45624 Fixed Costs (\$/month):4641, 5353, 5512, 5926 Material Loss: 2% per month
Building	Capacity (dry Mg):5040 Fixed Cost (\$/month): 6400 Material Loss:0.5% per month
Silo	Capacity (dry Mg): 7396 Fixed Cost (\$/month):11950 Material Loss:0.25% per month
Pellets:	
Building	Capacity (dry Mg): 9365 Fixed Cost (\$/month):6400 Material Loss: 0%
Silo	Capacity (dry Mg): 19726 Fixed Cost (\$/month):11950 Material Loss: 0%
Gate Price:	
Chips	\$88/dry Mg
Pellets	\$220/dry Mg
Demand at Conversion Facility	180,000 dry Mg/yr

a Wu et al., 2011

b *Ecowillow*, 2014

c AHC, 2014

d Norman and Oscarsson, 2002

e Pantaleo and Shah, 2013

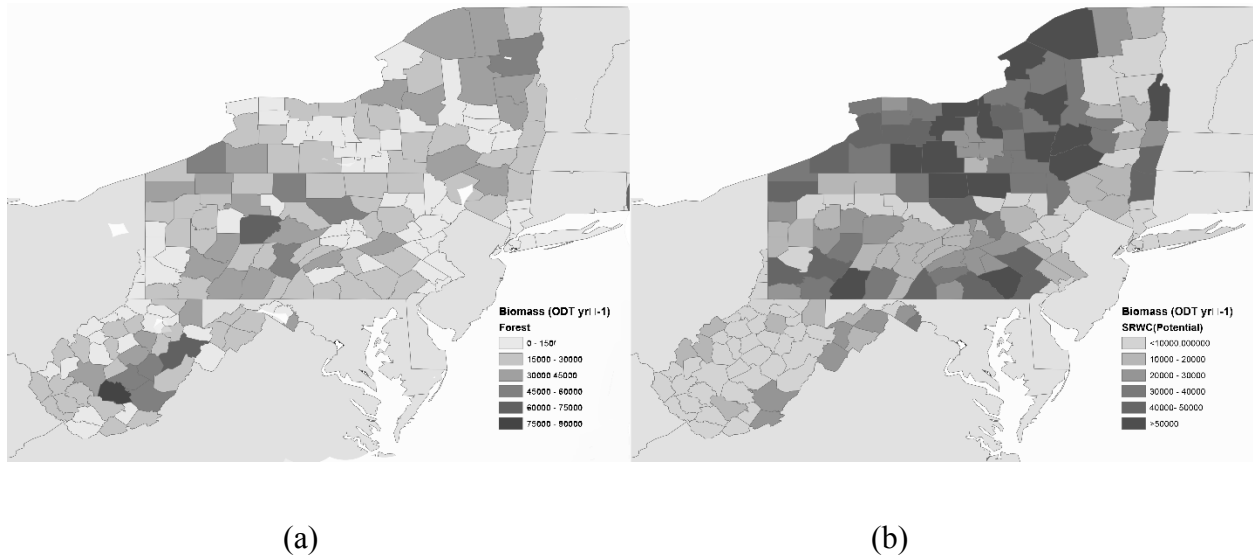


Figure 2-2 Biomass quantities and potential facility location candidates, (a) Forest Biomass, (b) SRWC

The base scenario for the model considered delivering biomass to facilities that required 180,000 dry Mg (200,000 odt) per year, the assumptions that are used are listed in table 2-1. Each county in the study area was considered a potential biomass supply location and it was also assumed that the feedstocks were aggregated to the centroid of the county (Figure 2-2a and 2-2b). Candidate biomass facility locations were selected from census designated places in each state, and each candidate was selected based on population and distance between the nearest neighboring candidate (Figure 2-3). The minimum distance between candidates is 120 km (75 miles) Euclidean distance.

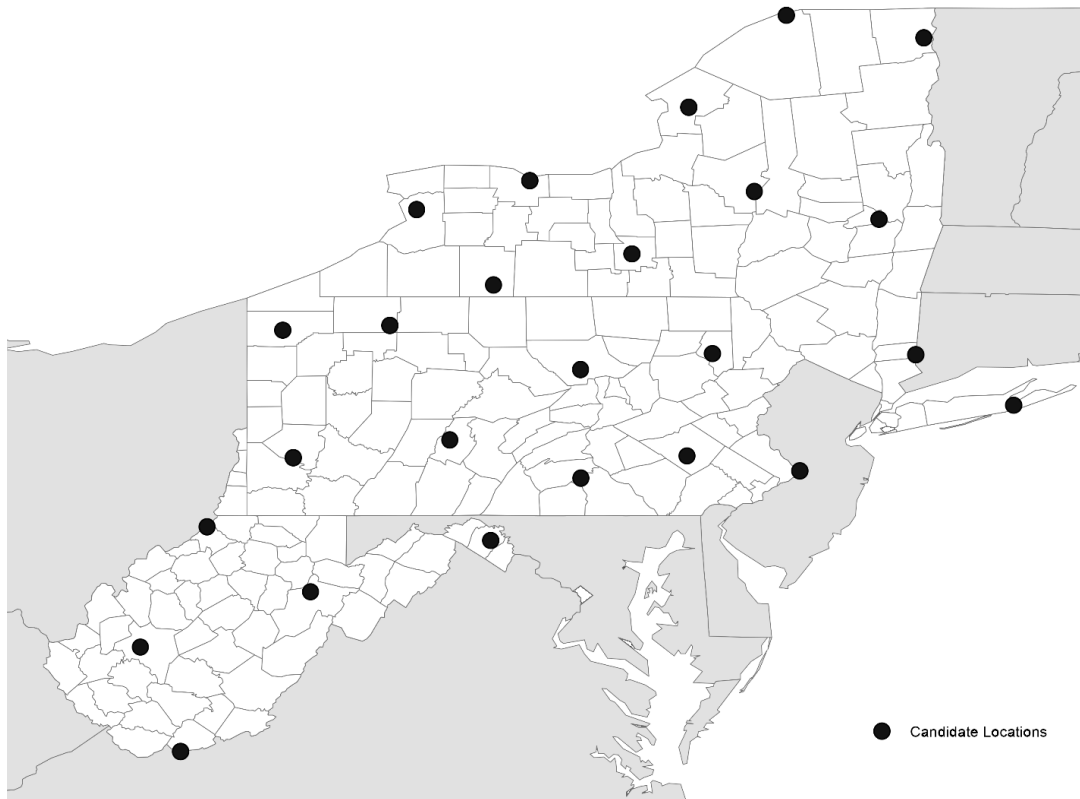


Figure 2-3 Locations of Candidate Facilities within the Study Area.

There were two harvesting systems that were considered for forest residue and a single harvesting system that was considered for SRWC. Forest residue harvesting systems were a grapple skidder system for loose residue and a grapple skidder-chipper system that for forest chips. SRWC were assumed to be harvested using a modified agricultural harvester with a specially designed header for the harvest of bioenergy crops. The production cost of each machine was taken from previous studies. The productivities and cost of the forest harvesting systems were taken from Wu et al. (2011) and adjusted to represent the harvesting cost per oven dry ton. The productivity and cost of the SRWC harvesting system was defined using the

Ecowillow model version 1.7 by SUNY ESF (*Ecowillow*, 2014). The output of the Ecowillow model provides harvesting cost per oven dry ton.

Transportation was assumed to be completed by tractor trailers with a maximum payload of 22.7 Mg (25 tons). Based on the bulk density of the materials it was assumed that chips and pellets would utilize the entire payload capacity of the trailers while loose material would only provide a payload of 15.9 Mg (16.6 tons). The distances between the feedstock sources and the facility locations, as well as the distances between facility locations were determined using the ArcGIS 10.2 Network Analyst, origin-destination cost matrix tool. Detailed transportation networks were created from OpenStreetMap data (Open Street Map, 2014). The cost of transporting biomass feedstocks is dependent on both the bulk density and the moisture content of the material. Table 2 lists the transportation rates adjusted for moisture content in $\$ \cdot \text{Mg}^{-1} \cdot \text{km}^{-1}$ for each of the three considered material forms.

Table 2-2 Transportation rates for considered feedstocks.

Material	Transport Rate $\$ \cdot \text{Mg}^{-1} \cdot \text{km}^{-1}$
Loose material	0.168
Chip	0.106
Pellet	0.081

The processing options that were considered for the analysis were: centralized chipping and pelletization. The use of centralized chipping was chosen as an alternative since the productivity is higher and the per unit cost of producing chips is lower in comparison to in-woods chipping (Rauch and Gronalt, 2010; Tahvanainen and Anttila, 2011). Centralized chipping requires a large initial investment in material handling and conversion equipment. The

large investment leads to a higher fixed cost per month for the chipping operation. The variable cost based on the volume of chips is assumed to be \$3.50 per ton (Norman and Oscarsson, 2002). Pelletization was considered as a method to improve transportation and storage characteristics of the feedstocks, as the bulk and energy density is increased and pellets are able to be stored for long periods without experiencing degradation (Pantaleo and Shah, 2013). The assumed capacity of the pellet plants is the average size of pellet production facilities in the Northeastern United States, approximately 50,000 tons per year (Biomass Magazine, 2014). The fixed cost of pellet plants of this capacity is approximately \$27,400 per month, with a variable cost of \$61.65 per ton (Pantaleo and Shah, 2013).

There are three types of storage that is being considered for wood chips and two types that are being considered for wood pellets. For wood chips, the types of storage are open air storage of different capacities; as well as covered storage and silo storage. Pellet storage options include building and silo type storage, as pellets cannot withstand precipitation. The amount of dry matter loss differs with each type of chip storage process, the fixed cost, capacity and associated material losses are presented in Table 2-1.

The model is also constrained by the requirements of feedstock material needed by the conversion processes. There are five gate demand levels in this model which assumes that the processes can use either chips or pellets as a feedstock. The material requirements for both chips and pellets as well as the equivalent size for electricity production and liquid fuels production are given in Table 4.

Table 2-3 Material demands for each conversion level.

	Electric Production (Mw)	Liquid Fuel bbl * day ⁻¹	Chips Mg * month ⁻¹	Pellets Mg * month ⁻¹
Extra Small	5	145	4511	3817
Small	10	360	8986	7630
Medium	20	720	16000	13538
Large	50	1000	40000	33847
Extra Large	100	2000	80005	67695

Sources:(Badger, 2002; Perlack et al., 2011)

2.4 RESULTS AND DISCUSSION

2.4.1 Base Scenario

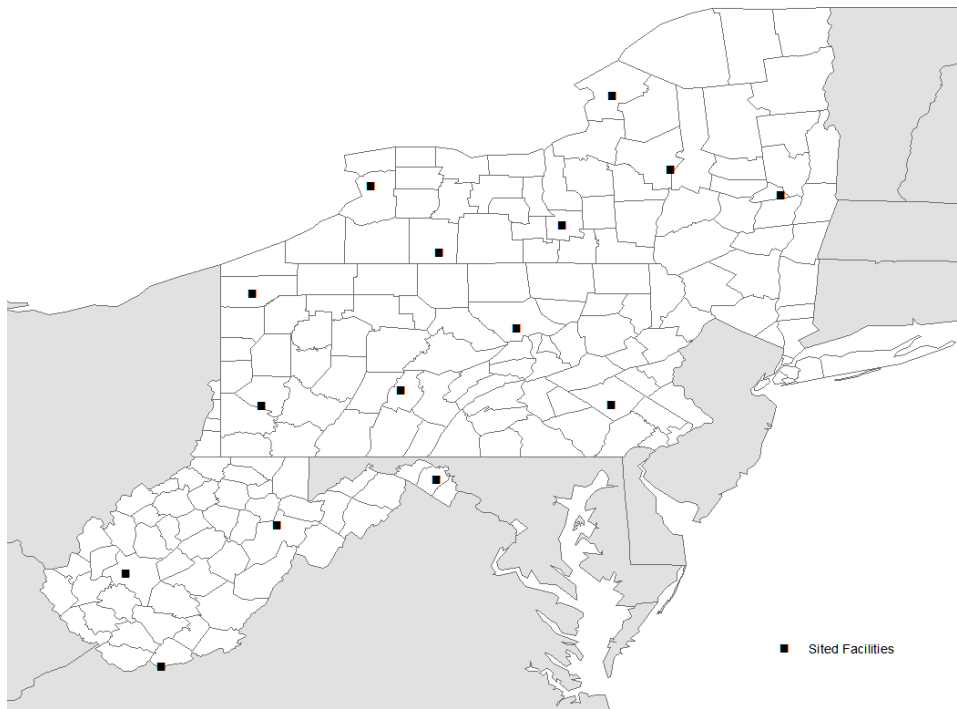


Figure 2-4 Location of Sited Facilities under Base Assumptions.

The optimization of the base scenario of a biomass plant demand of 180,000 dry Mg of woody biomass per year was summarized by the delivered cost, average hauling distance and optimal plant locations. The results show that in the three-state there are 15 plants that are sited under optimality. The locations of the facilities are shown in figure 2-4. The distance that material needed to be transported to reach the mill ranged from 3.21 km (2.24 mi) to over 292 km (181 mi) with the overall average transport distance being 71.65 km (44.52 mi). The average delivered cost for the 15 plant locations was found to be \$72.58 per dry Mg (\$65.99 per odt), with a range from a low of \$64.69 per dry Mg (\$58.81 per odt) to a high of \$98.31 per dry Mg (\$89.37 per odt) (table 2-4). The results show that the candidates that had the highest transport distances also have the highest delivered cost. In fact, some of the facilities had a portion of their feedstocks that had a delivered price that was higher than the assumed gate price, suggesting that it was necessary to pay a premium for this material. Suppliers will not generally deliver material to a facility if they are going to take a loss, instead the facilities may need to pay a distance bonus to acquire the material that is needed for operation when it is not possible to procure it at market price.

The base scenario proposed the inclusion of storage and processing options to improve the cost structures involved in the biomass supply chains. The results showed that while there are efficiency improvements leading to lower per unit costs, associated with the use of centralized chipping and pelletizing facilities the investment that is required actually impairs the economics of bioenergy feedstock production. This is the same result as found by Pantaleo et al. (2013) who stated, "The higher cost...makes this choice not profitable, despite its lower transport and storage cost, and higher energy conversion". Potentially if the required demand is high enough or if the

premium paid for these feedstocks is high enough then these or similar technologies would be employed.

Table 2-4 Transport Distances and Delivered Cost for Facilities Sited in Base Scenario.

Candidate	Transport Distance			Delivered Cost		
	Min	Avg	Max	Min	Avg	Max
Altoona	8.30	62.99	107.07	65.24	71.59	76.72
Bethel Park	20.16	69.77	180.39	66.62	72.38	85.24
Bluefield	27.41	89.24	154.81	67.46	74.64	82.27
Charleston	15.25	78.54	155.78	66.05	73.40	82.38
Cheektowaga	20.62	78.21	235.09	66.67	73.36	91.60
Elkins	18.37	62.62	137.49	66.41	71.55	80.25
Ithaca	3.60	60.94	154.36	64.69	71.36	82.21
Martinsburg	5.23	71.26	181.59	64.88	72.55	85.38
Meadville	5.32	56.99	129.43	64.89	70.90	79.32
Reading	9.48	64.27	292.80	65.37	71.74	98.30
Schenectady	12.61	73.29	204.95	65.74	72.79	88.09
Utica	27.50	83.10	193.31	67.47	73.93	86.74
Watertown	8.17	102.46	235.11	65.22	76.18	91.60
Wellsville	19.79	62.11	129.78	66.57	71.49	79.36
Williamsport	13.48	58.68	118.92	65.84	71.09	78.09

Conversely, storage is employed in all cases to take advantage of the relatively lower cost of SRWC feedstocks, the more of the low cost feedstock that can be stored results in less consumption of the higher cost feedstocks reducing the overall costs associated with production. Storage was utilized for the base scenario, in total 13.09% percent of the material resided in storage before being used for conversion. The use of storage allowed for the use of material that came from SRWC to be utilized well beyond the harvest window for the material. Fourteen of the sited facilities utilized outdoor, open storage and one used building storage. In all cases, the storage facilities were co-located with the conversion facilities and the storage capacity was filled by the third month, which coincides with the end of the SRWC harvest window, and

gradually decreased until the ninth month when the supplies were exhausted. The lone facility that utilized building storage was located in Charleston, WV. This facility is located in an area that has one of the highest availabilities of forest biomass and the lowest availability of SRWC (figure 2-2). The access to feedstocks that are less temporally dependent removes the requirement for storage, allowing for storage that is smaller in capacity.

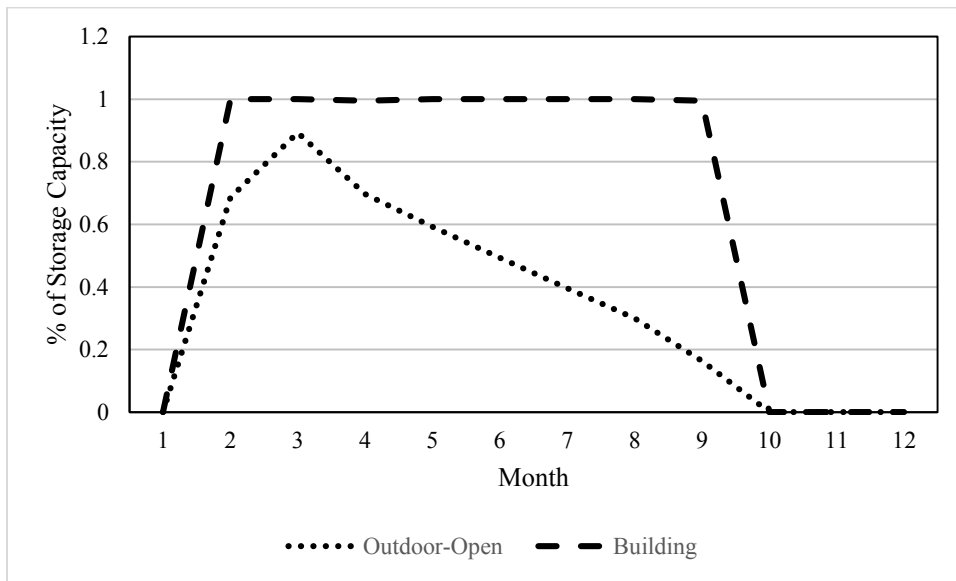


Figure 2-5 Percentage of Storage Capacity Utilized per Month.

The average delivered cost of the biomass feedstocks for the base scenerio ranged between \$70.91 and \$76.19 odt⁻¹, which is reasonable compared to past research by Grushecky et al.(2007) who estimated the true price to be within a fairly wide range of \$29.7 to \$97.1 per dry Mg when considering the entire process including felling to delivery to the conversion facility but is higher than the range provided by Botard and Gallagher (2014) who reported a range of \$8.44 to \$47.91 odt⁻¹ for extraction only using of conventional harvesting systems similar to the systems that are employed in this study. Additionally, the cost is also less than the target set by the U.S Department of Energy of \$88 per dry Mg (Perlack et al., 2011). The

reported cost while being lower than the target price, is dependent on SRWC, which has not been established widely throughout the region and does not include required profit or payment for risk for the producers, leading to a price that remains above the target.

2.4.2 Sensitivity Analysis

2.4.2.1 Material Availability

In addition to the base case analysis of a 10% conversion of marginal land to SRWC, the impact of different levels of feedstock availability were also examined. For the analysis scenarios were examined in which there is 0%, 5% and 15% conversion to SRWC and also the case where there is no available forest derived woody biomass material (figure 2-6). The 0% case, or only have access to forest derived biomass was found to be the highest costs case with an average delivered price of \$81.49 per dry Mg (73.34 per odt) with a range between \$72.40 and \$100.74 per dry Mg (\$65.61-\$90.67 per odt). The lowest delivered cost was found in the case where 15% of the marginal land was utilized to grow SRWC. The delivered cost for the 15% conversion case was \$71.28 per dry Mg (\$64.15 per odt) a reduction in delivered cost of 1.8% when compared to the base scenario. Alternatively, when the availability of SRWC material was reduced 5% from the base scenario, the delivered price was increased by 4.3% to \$75.71 per dry Mg (\$68.14 per odt).

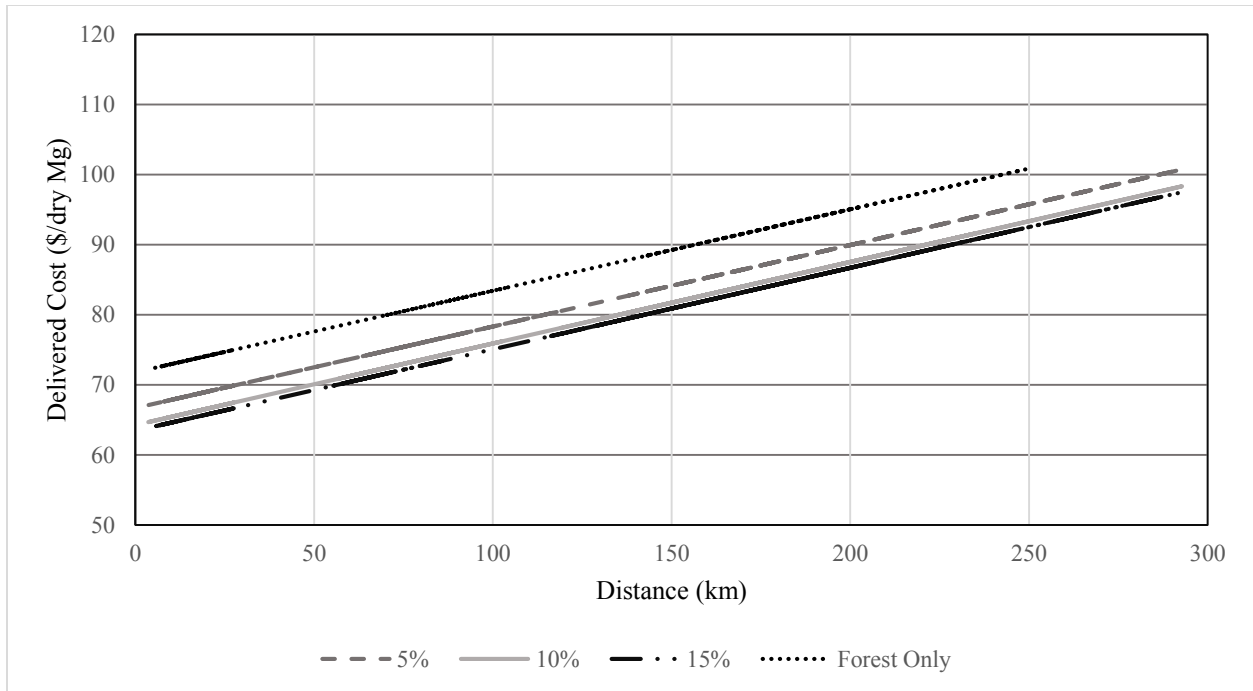


Figure 2-6 Delivered Feedstock Cost for 0%,5%,10% and 15% Conversion of Marginal Crop Land by Transport Distance.

The availability of SRWC material also had an effect on the procurement area (i.e the distance that the material was transported) (figure 2-7). As more SRWC material was available the distance that needed to be traveled to procure the material was reduced. In the forest only scenario, the average distance traveled to deliver material was approximately 83.5 km, increasing the amount of land in SRWC to 15% decreased the travel distance by nearly 20% which equates to a reduction in delivered price by \$1.87 per dry Mg (\$1.70 per odt). At the base analysis level of 180,000 dry Mg per year it would equate to an annual savings of more than \$336,000 per year.

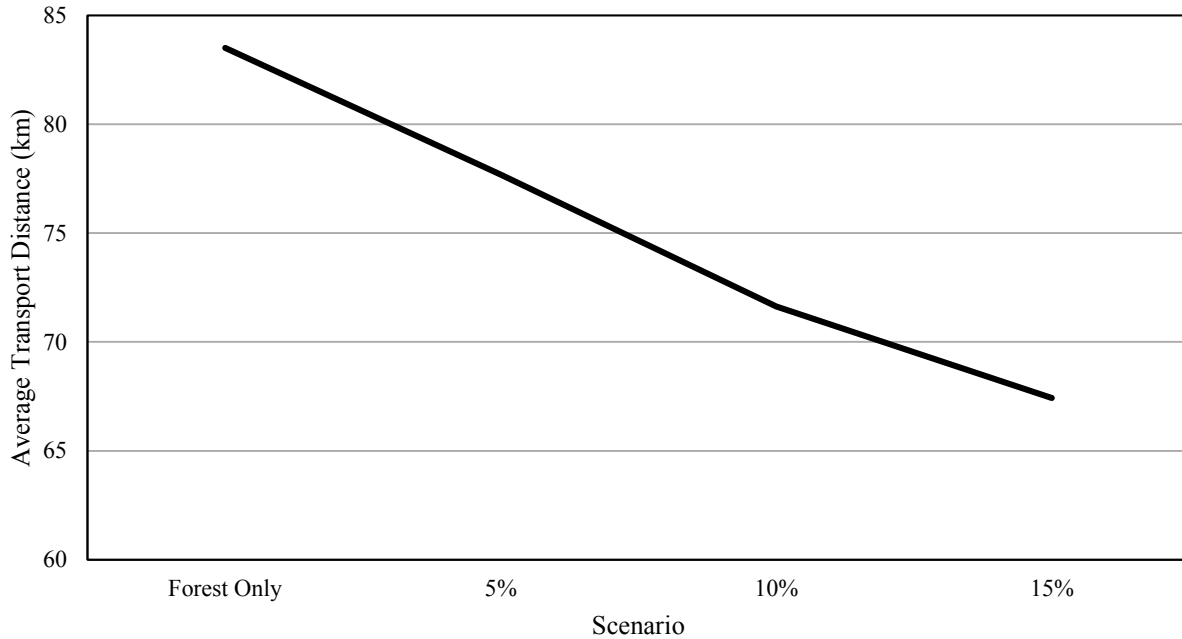


Figure 2-7 Average Transport Distance by SRWC Availability Scenario.

Similarly, the amount of available SRWC material had a positive relationship with the reduction of harvesting cost. Results showed that as the availability of SRWC material increased the average harvesting cost for the delivered material decreased. This was to be expected as the harvesting equipment has been designed especially for the harvest of SRWC, which provides an edge in operational efficiency and production over the equipment utilized to harvest forest derived biomass. It was seen in the results that as the quantity of SRWC material increased the proportion of the total harvest that was made up of SRWC also increased.

2.4.2.2 Harvesting & Extraction Cost

The cost of harvesting and extraction of biomass feedstocks is not a fixed parameter. Changes in technology and/or regulations governing biomass removal have the potential to either decrease or

increase harvesting costs. In the analysis, the cost to harvest and extract were varied between 10% below and 10% above the base scenario. It was assumed that the changes that resulted in the changes to the harvesting cost did not change handling properties or affect operations along the supply chain.

The results showed that the delivered cost of biomass feedstocks is not very sensitive to changes in harvesting cost alone, since the change in delivered cost is only a fraction of the change in harvesting cost. In fact, the change in delivered cost was found to range from 30% to 40% of the change in cost, decreasing as travel distances get longer. Since it was assumed that the handling and transportation characteristics were not affected the reduction in cost begins to be diminished as transportation distances get longer, as harvesting cost account for decreasing proportion of the total cost (figure 2-8). For example, from the results it was found that when there is a 10% reduction in harvesting cost and the material is transported 10 km then the total cost reduction is 4 percent; for the same harvesting cost reduction, if the material is transported 150km then the total delivered cost is reduced by 3.3%. While any cost reduction is welcomed in the effort to provide cost effective renewable energy feedstocks, changes to work methods and modifications to equipment that only result in modest cost improvements, will not likely be enough to result in substantial reductions in cost by the time that the material arrives at the conversion efficiency.

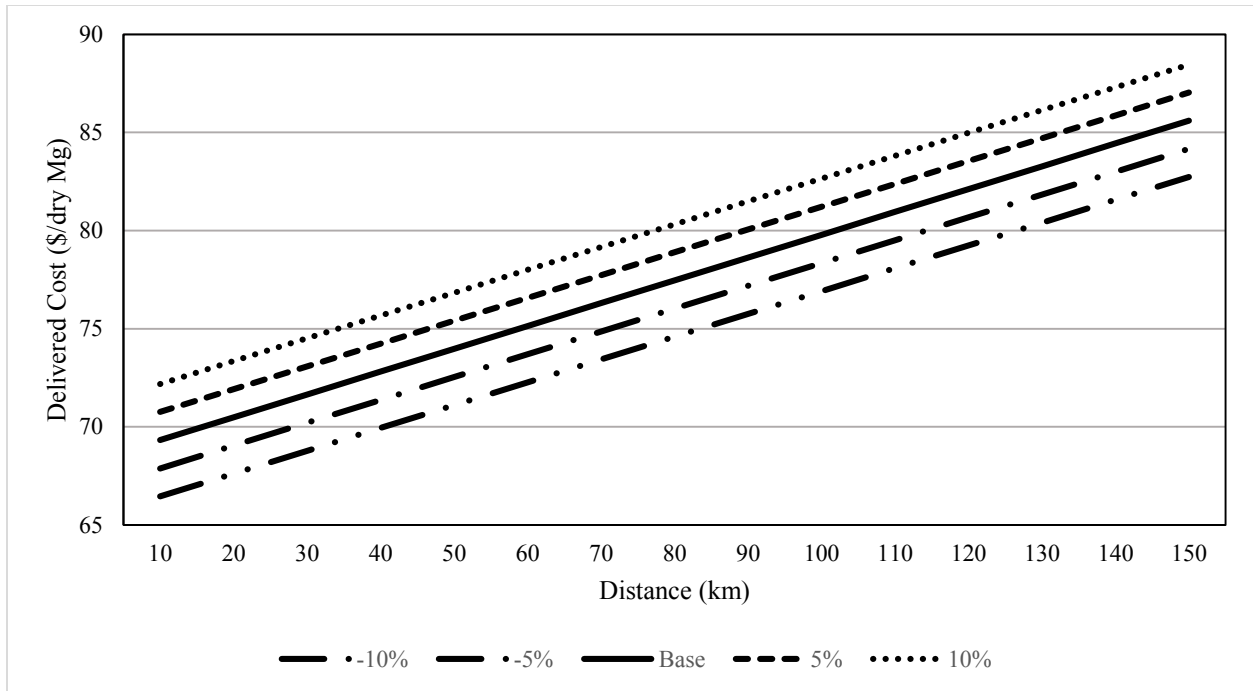


Figure 2-8 Sensitivity of Delivered Cost to a Reduction in Harvesting Cost by Distance.

2.4.2.3 Moisture Content

In transportation, the weight of the water reduces effective payloads. For example: assuming that a truck has the capacity of 25.2 tons of wood chips, at 50% moisture content wet basis, the payload of oven dry material would be 12.6 Mg. Reducing the moisture content by 20% would increase the payload by 4.5 Mg of oven dry material. For this reason, moisture content can have a significant impact on the delivered price of bioenergy feedstocks. Distance is a contributing factor that moisture content has on the impact of the delivered cost of feedstocks (figure 2-9). When transport distances are small (below 75 km), little difference is noticed as difference between the 10% moisture content and 50% moisture content is \$5 per dry Mg, or less. When the distances are greater the difference is more pronounced, for example at 300 km, the

difference in price between 10% moisture content and 50% moisture content would be approximately \$22 per dry Mg. Typically, material harvested in the Northeastern United State ranges from 55% moisture content to 40% moisture content, allowing material to dry in the field before transport may lead to an overall reduced cost. Studies have found that drying material in field lead to a cost reduction of approximately 20% on a dry material or energy basis and reduce self-heating and dry matter loss (Jirjis,1995;Cutshall et al., 2013). In field drying will lead to there being large amounts of dry material left on the ground, increasing fuel loads and potentially fire risk; but the climate in the northeastern United States makes the risk of fire minimal due to the relatively high amounts of precipitation and higher levels of relative humidity.

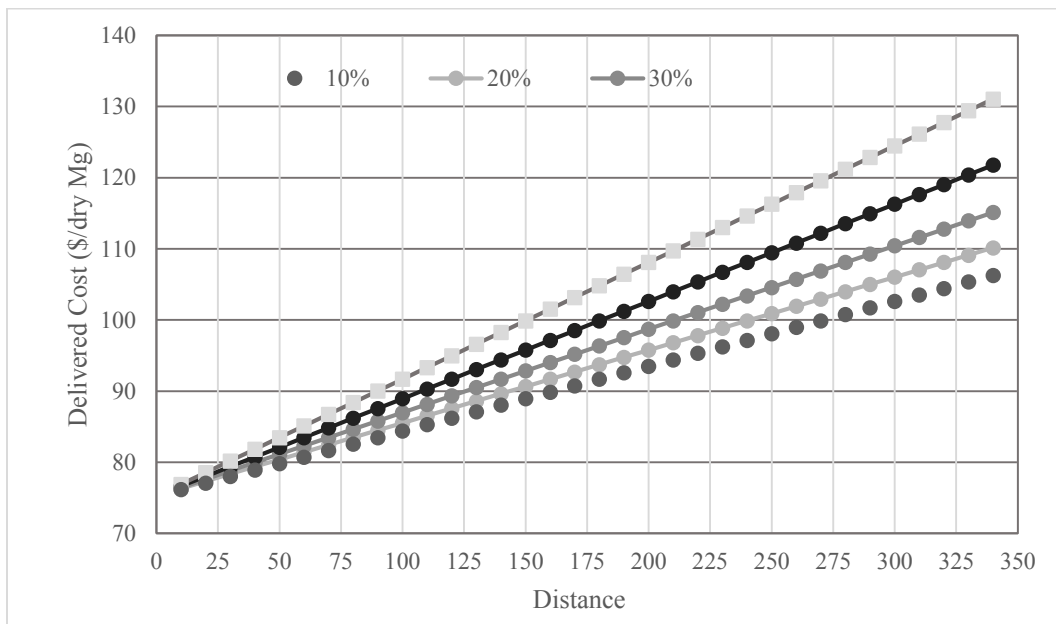


Figure 2-9 Sensitivity of Delivered Cost to Moisture Content and Distance.

2.4.2.4 Facility Demand

The scale of a facility will dictate the quantity of material that is needed for the facility to operate. Additionally, due to “economies of scale”, it is often suggested that the plants that are to be built should tend to the larger size rather than smaller (Uslu et al., 2008). The down side of this pattern of thinking, in terms of bioenergy, is that biomass feedstocks are not as energy dense as traditional energy sources and transportation is a limiting factor in their economic feasibility (Caputo et al., 2005; McKendry, 2002). The size of the facility was found to have an impact on the delivered price of the feedstocks and the number of facilities that are able to be sited in a region (table 2-5). The smallest demand level that was examined was 49,500 dry Mg per year, the average delivered price was \$69.58 per dry Mg (\$62.62 per odt) with a range between \$66.46 per dry Mg (\$59.81 per odt) and \$73.97 per dry Mg (\$66.57 per odt) for the 24 facilities that were sited. The highest delivered cost was found for the highest demand level (900000 dry Mg), with an average cost of \$81.28 per dry Mg (\$73.15 per odt). In addition at the highest level there were only two facilities able to be sited.

Table 2-5 Transport Distance, Delivered Cost and Number of Facilities Sited for Differing Demand Levels.

Demand Level	Transport Distance(km)			Delivered Cost (\$/dry Mg)			# of Facilities
	Min	Avg	Max	Min	Avg	Max	
49500	19.50	46.37	84.15	66.46	69.58	73.97	24
90000	39.55	68.11	127.67	70.95	74.27	81.19	24
180000	56.97	71.63	102.46	70.91	72.61	76.19	15
450000	101.19	106.13	109.12	76.13	76.71	77.06	5
900000	145.29	145.90	146.52	81.21	81.28	81.35	2

The average transport distance and average cost for feedstocks each increased as the demand of the facilities increased. This is to be expected as when more material is needed the distance that must be traveled is also greater. Additionally, since transportation cost is directly related to hauling distance, as distance increases the delivered cost will go up. Examination of a curve that depicts the relationship between facility size and distance traveled (Figure 9), a change in slope of the curve is noticeable between the medium and extra-large demand categories. The change in slope is an indicator that as the facility demand surpasses the 180,000 dry Mg per year threshold that the material is becoming scarcer and the distance traveled increases at a faster rate. Further evidence of this can be seen by examining the resource utilization at the various demand levels. Figure 10, displays the resource utilization as a percentage of the total available resource. It is easily seen that utilization peaks at medium demand facilities. For facilities that require less material, their entire demand is available within relatively close proximity of the facility. The facilities that require more material, forces competition between the facilities leading to fewer facilities and a larger portion of the area that contains material but not in sufficient quantities to support the required demand.

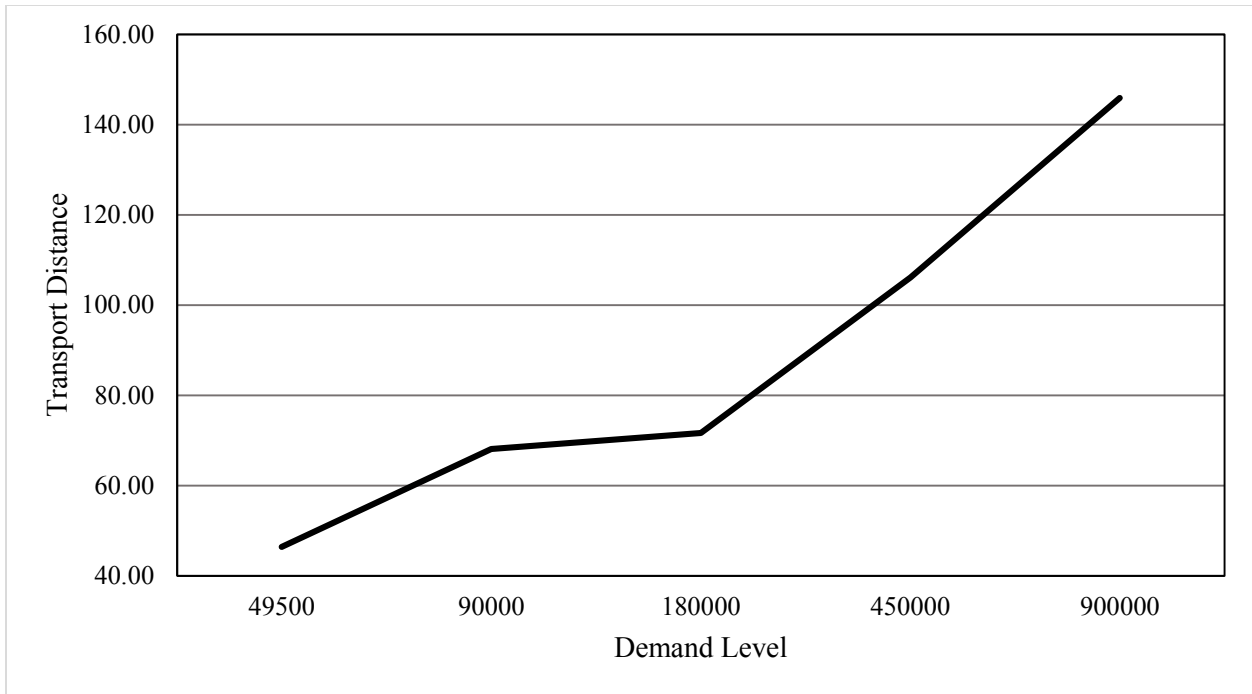


Figure 2-10 Average Transport distance by Demand Level.

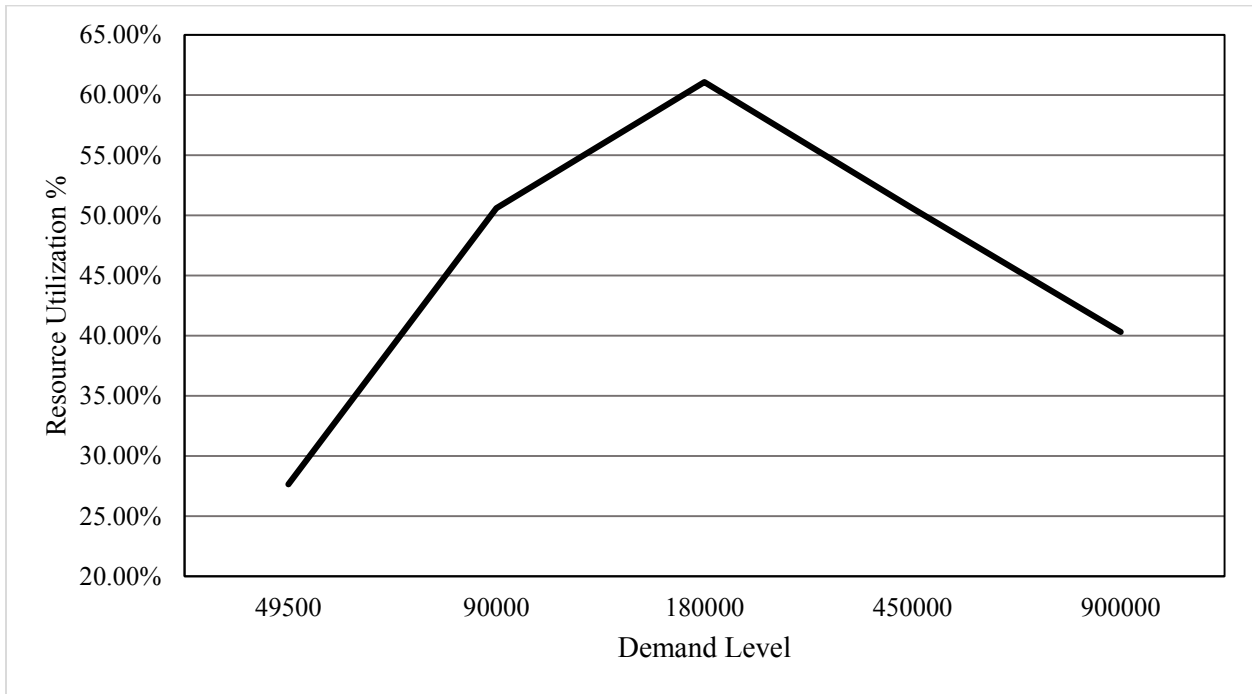


Figure 2-11 Resource Utilization by Demand Level.

While it is likely that a variety of facility sizes will be utilized as the bioenergy industry develops. In the case that a single demand level is required then the optimal size is a facility that requires 200,000 odt yr⁻¹, based on resource utilization and total output. For example the region can support 24-200,000 odt yr⁻¹ which is roughly equivalent to the production of 480 MW of electricity production. For a 500,000 odt yr⁻¹ demand, the region can support 8 facilities, equating to 400 MW of electricity production. Similarly, if the demand is required to be 1,000,000 odt yr⁻¹ then there can be only 3 facilities supported with a production of 300 MW of electricity.

2.5 CONCLUSIONS

The mixed integer programming model that has been developed can be used to identify locations for potential development of biomass energy facilities as well as defined the supply chain configuration for each facility; under different supply and demand scenarios. The base-case scenario, showed that based on feedstock availability that it is possible to have a bioenergy facility in 15 of the potential candidate locations at a price range of \$70.91-\$76.19 per dry Mg. With smaller demand levels it is possible to expand the number of facilities to 24 of the 25 potential candidate locations and the cost is also reduced to \$66.46-\$73.97 per dry Mg. Conversely when the demand exceeded 180,000 dry Mg per year (200,000 odt per year), cost dramatically increased to over \$80 per dry Mg and procurement areas grew rapidly; doubling the size of the procurement area in the base scenario, leading to fewer facilities that were able to be sited. The candidate facilities were sited based on even coverage of the study area and relatively

uniform spacing between locations. These locations may or may not represent true best locations for facilities, based on current infrastructure, local and regional incentive programs, competing industries, etc. It is for this reason that it can only be stated that the location of a facility is located in the area that is represented by a 37.5 mile radius around the candidate point; and that secondary analysis should be conducted to account for the additional factors associated with final facility locations.

Developments in technology leading to large scale adoption of these technologies may lead to increased competition and resulting in an increase in the price of the raw materials. Conversely, if development progresses specialized technology will be developed to improve the efficiency in which the materials are handled, which may lead to a reduction in the delivered cost of energy feedstocks. In addition to demand and technology changes there are other factors that may impact the cost of feedstocks, such as weather, disease, etc.

The utilization of the biomass resource indicates that it may be better for distributed production scenarios that included multiple demand levels over scenarios that had a fixed demand level. Woody biomass harvesting, transportation and processing are labor intensive, and the spatial distribution and relatively low bulk density limit the economical transportation distance of these materials. These two factors suggest that future woody biomass energy markets will be distributed and region specific. As a result, the potential will exist for the creation of jobs in regions that adopt these technologies. It is estimated that for each megawatt of power produced from wood that at least four jobs are created, not including additions due to increased transportation needs and operation of the conversion facility (Byrnett et al., 2009).

This study illustrated that the inclusion of SRWC into woody biomass supply chains that it will be possible to reach the targets that have been set by the US. Department of Energy. This means that meeting the goal is incumbent on the establishment of SRWC throughout the area. Additionally, this study provided an example of how optimization of facility site and scale can be used to determine how well the proposed facilities will utilize resources and identify the necessary procurement areas. This information can be used as a method of comparison, to examine how improvements in feedstock yield, harvest technology and processing and conversion techniques are improving the economics of bio-energy in the region. Additionally, the model can be adapted for use in other regions as well as be scaled for assessments of sub-regions.

Acknowledgements

The authors acknowledge the funding support for this study by the United States Department of Agriculture, National Institutes of Food and Agriculture and the Northeast Warm-season/Woody Biomass Consortium (Grant No. 2012-68005-19703).

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**3 ANALYSIS OF DRIVING FACTORS AFFECTING WOOD BASED
BIO-ENERGY FACILITY DEVELOPMENT USING A SPATIAL
PROBIT MODEL**

ABSTRACT

Concern about the sustainability of traditional fossil fuel energy sources has increased the development of alternative energy resources. In the temperate forest regions of the United States the most promising alternative is the use of woody biomass. Woody biomass includes residue from forest products and forest management operations, clearing of land for the development of coal and natural gas, and dedicated energy crops. In addition, the use of woody biomass for energy has been suggested as a way to improve rural economies through job creation, reduction of energy costs and regional development. This study examined existing wood using bio-energy facilities in the northeastern United States to define the drivers of establishment of bio-energy projects. Using a spatial econometric framework, a spatial autoregressive probit model was estimated based on the Bayesian methods to define the factors that impact the location of wood using bio-energy facilities in the United States.

3.1 INTRODUCTION

According to projections from the Energy Information Administration (EIA), worldwide energy consumption is expected to increase from 495 quadrillion BTUs in 2007 to 739 quadrillion BTUs in 2035, an increase of 49%. This projection is mostly attributed to increased energy demand in China and India, which is expected to expand by more than 110% over the next 25 years. During the same period, the demand for energy in North America is projected to increase by 9.6%(EIA, 2010).

In the U.S., the production of electricity relies heavily on fossil fuel resources, with nearly 66% of the electricity produced coming from fossil fuel sources(EIA, 2010) . The burning of fossil fuels contributes to an increase in the atmospheric concentrations of greenhouse gases

which has been linked to global climate change and an increase in extreme weather events. Additionally, energy dependence on fuel rich countries and the fear of dwindling energy supplies has led to increased concerns about future energy security. For this reason many countries are searching for renewable and sustainable alternatives to conventional fossil fuel production which can be implemented using local resources.

Woody biomass, which has historically produced more than 14% of the world's energy, is one of the largest and most sustainable energy resources (McIlveen-Wright et al., 2001). Woody biomass, which includes residues from: timber harvest, residues from primary and secondary wood processing as well as tree removals during fuels reduction, pre-commercial thinning, residues from surface mining and shale gas drilling and short rotation woody crops; has the potential to be a feedstock for both liquid fuels and the production of electricity (Bridgwater et al., 2002; Caputo et al., 2005; Kaylen et al., 2000; Tembo et al., 2003; Thek and Obernberger, 2004; Wang et al., 2006). The potential worldwide woody biomass supply is estimated to be able to produce 150 EJ/yr or 1.43 times the annual energy consumption of the United States (Faaij and Domac, 2006). In the United States, temperate forests are located in the eastern and northwestern portions of the country, and are estimated to be able to produce approximately 57 million dry tons of biomass annually at a price of \$66.14 per dry tonne (\$60 per dry ton) (Perlack et al., 2011). That material could be used to produce approximately 88 billion kWh of electricity or 12.87 billion liters (3.4 billion gallons) of liquid fuel, based on 15.81 GJ per tonne (16 million Btu per ton) and 33% efficiency for electricity and 227.12 liters (60 gallons per dry ton) (American Physical Society, 2013; Perlack et al., 2011). Wood has been shown to produce much lower levels of air pollution than coal. This is because the sulfur and nitrogen content of

wood is low which produces negligible amounts of SO_x and NO_x emissions. In addition, the combustion of wood also produces much less CO₂ than the combustion of coal (McIlveen-Wright et al., 2001). The use of biomass also promotes energy security having multiple fuel sources increases the power grids ability to respond to resource supply disruptions (Brown and Mann, 2008).

While environmental benefits and domestic energy security are touted during the development of bio-energy projects, the real drivers are the potential for job creation, improved industrial competitiveness and regional development (Domac et al., 2005). Woody biomass harvesting, transportation and processing are labor intensive. Additionally, the spatial distribution and relatively low bulk density of woody biomass limits the economical transportation distance of these materials. These factors suggest that future woody biomass energy markets will be distributed and region specific. As a result, the potential will exist for the creation of jobs in regions that adopt these technologies (Gan, 2006). It is estimated that for each megawatt of power produced from wood that at least four jobs are created, not including additions of jobs due to increased transportation needs and operation of the conversion facility (Byrnett et al., 2009). A study conducted by ECOTEC Research and Consulting Ltd/Directorate General for Energy, European Commission (1999) in the European Union estimated that doubling the use of bio-energy will lead to the creation of 900,000 jobs of which 500,000 will be in the agricultural sector. While the ECOTEC study included only the direct and indirect impacts of bio-energy projects on employment, similar projects can also be expected to contribute significantly to the local and regional economies by increasing economic growth through business expansion, import substitution, improved efficiency, energy security and diversification.

The importance of industry location is a concept that was theorized beginning in the late 19th century by Ross (1896). In his work, “The location of industries”, Ross proposed a theory that geographic location gave economic and cost advantages to certain industries. More specifically, the availability of labor, raw materials, transportation and the ability to exchange information are factors that influence the locations of industries (Marshall and Marshall, 1920; Predöhl, 1928). Consequently, industries tend to locate where the access to raw materials, the cost of inputs and technical restrictions are at optimal levels (Rawstron, 1958; Renner, 1947). While initial location theory appeared to explain the rationale that goes into industrial location decisions, in terms of economics; it was not very useful for empirical analysis as it focused on geometry instead of economics and did not produce models that could be used to test hypotheses (Krugman, 1997).

New Economic Geography and Cluster Theory have emerged as two improvements on Location theory. New Economic Geography proposes the use of a model that explicitly include factors that draw or push industry to or from a location (Fujita and Krugman, 2003; Krugman, 1990). Similarly, Cluster Theory suggests that similar businesses group together where there a competitive advantage is experienced (Porter, 1998). In addition to these theories, the introduction of new statistical tools has allowed for empirical analysis of industry’s location choices (Aguilar, 2009).

Spatial econometric methods, specifically the use of the spatial probit model, has been used to investigate the impact of location on binary choices (i.e. yes or no, build or do not build, etc.). Altman et al.(2007) used a probit model that contained a spatial factor to examine a firm’s decision to purchase inputs internally or externally. Aguilar (2009) employed the use of a spatial

autoregressive probit model to examine the lumber industry in the southeastern United States. He found that in addition to the factors of stumpage price, availability of labor, access to transportation, land values, availability of resources and energy costs that the spatial location of the facilities was an important predictor of the occurrence of a lumber industry facility. Additionally, he carried the analysis one step further using the developed model to predict additional locations where the industry could expand. Stewart and Lambert (2011) used a bivariate probit regression to examine the investment activity of ethanol plants in the United States. In their investigation, they looked at the presence (or announcement) or absence of ethanol plants in the contiguous 48 states at a county level. The differences between facilities that had been built versus facilities that had been announced were compared. They found that that proximity to feedstock supply and road density were important factors for the plants that had been built, but not so for announced facilities. The early plants had fully utilized the prime locations and new facilities are being allocated to more marginal areas. Additionally, they found that the spatial dependence between firms was negative, indicating that if a facility already existed near the location it was less likely to be suitable for new locations. Similarly, Fortenbery et al. (2013) carried out similar analysis for the siting of biodiesel refineries. Their analysis found that while policy mandates and incentives were driving factors, the presence or absence of other operating plants was not important in the siting of new facilities.

The factors that determine the choice of location for the development wood based bio-energy facilities, aside from feedstock availability and transportation, has not been a topic that has been widely explored in the literature. The majority of work that has been published focuses on the siting of facilities based on the minimization of delivered cost of the feedstock or

feedstock availability. While both cost and availability are two of the most important factors in the success of a wood using bio-energy plant, there are certainly additional factors that will influence the choice of one site over another.

The variety of factors that are considered drivers for renewable energy production suggests that the future development of bio-energy will take into account more than resource availability when choosing sites for construction. It is expected that through analysis of currently established wood based bio-energy facilities that it will be possible to identify factors that indicate high suitability for future development. This study aims to develop a better understanding of additional factors that lead to the installation of wood using bio-energy facilities by examining the relationship between a set of chosen explanatory variables and the location of current wood based bio-energy facilities. Therefore, the objectives of this study were to examine the locational drivers for the development of wood based bio-energy facilities.

3.2 METHODS

Study Area

The study area for this project included 12 states and a total of 299 counties in the northeastern United State (Figure 1). The Northeast already has a wealth of existing feedstocks and the potential to increase supplies in the future. There are currently between 1.35 and 25.64 million dry tons of woody biomass available per year in the northeast at a price between 60 and 90 per dry ton. It is also estimated that the region will be able to sustainably produce between 80.7 and 141.5 million dry tons of biomass per year, in the form of Short Rotation Woody Crops

and energy grasses, by the year 2030(Kaylen et al., 2000)]. The availability of these resources provide a competitive advantage for economic development(Bridgwater et al., 2002). Biomass harvesting, transportation and processing are labor intensive, and the spatial distribution and relatively low bulk density limit the economical transportation distance of these materials; leading to markets that are distributed throughout a region.

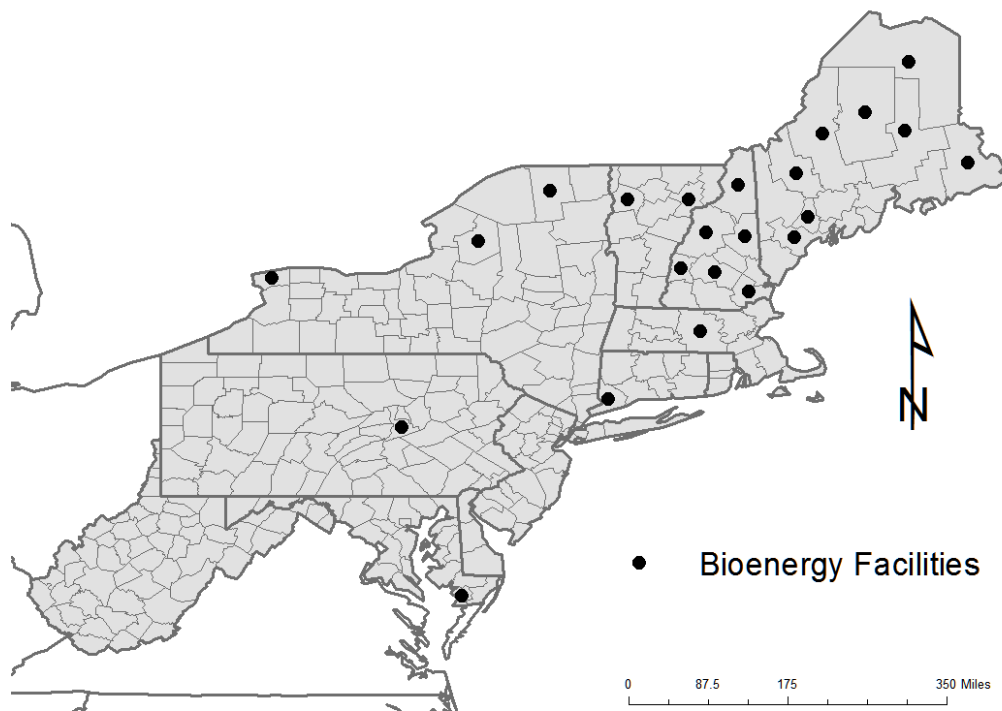


Figure 3-1 Location of wood using bioenergy facilities in the Northeastern United States.

Modeling Approach

It is assumed that similar resources are needed to those of the lumber industry, similar methodologies can be used for wood based bio-energy as have been used for the analysis of spatial behavior in the forest products industry. A methodology proposed by Aguilar (2009) on modeling the spatial behavior of the lumber industry was used in this study. The basic

assumption for any biomass energy projects is to maximize profits as a means to maximize utility. Profit maximization will be accomplished by the facilities locating in the counties that provide the highest levels of utility, given that the utility for each county is derived from a combination of characteristics (Lancaster, 1966). Additionally, it is assumed that there are a large number of sites available so that there is a variety in the combinations of the characteristics. Finally, it is assumed that the decision makers have full availability of information and the cost of establishment is equal across all locations.

Utility is an unobservable variable; as such, the presence of a bio-energy facility in a county, defined as a binary variable (1 if present; 0 if absent), will be used to represent the utility of a given county. This can be done because the model for a binary dependent variable derives the latent utility from an underlying latent variable model and is equivalent to the marginal benefit-cost based on the utility of siting a facility in a county versus another county (Aguilar, 2009). The utility of a site can be defined as function of a set of explanatory variables used for determining preference and can be expressed as:

$$y_i^* = X\beta_i + \varepsilon \quad (3-1)$$

Where y_i^* is a continuous variable representing presence or absence of bioenergy facilities, X is a vector of independent variables representing the factors that influence presence or absence of, β_i is a vector of parameters associated with the X vector, and ε is an error term. Since the net benefit or utility is unobserved, the dependent variable takes on a value of 1 if the net utility is positive and 0 if the net utility is less than or equal to 0. The goal of the binary response model is to define the probability that the dependent variable is equal to 1, given a set

of independent variables, referred to as a probit model. This can be modeled as follows:

$$P(y = 1|X) = G(X\beta), \text{ and } 0 < G(X\beta) < 1 \quad (3-2)$$

Where G is a nonlinear function that can only have values between zero and one.

Spatial econometric analysis

Spatial dependence, in terms of bioenergy facility location, is the situation where the likelihood of a facility being sited at a location is related to whether or not another bioenergy facility is located at nearby locations (LeSage and Pace, 2009). If spatial dependence is present in the data, the models that are used must take into account this factor, since it violates the traditional assumption of independence of observations. Spatial dependence is accounted for in the models by the addition of a spatial weight matrix. The spatial weight matrix is used to define which additional observations have an impact on the dependent variable. The weight matrix is used to spatially lag the independent variable as follows:

$$Wy = \sum_{i=1}^n w_{ij}y_j, j = 1, \dots, n \quad (3-3)$$

Where Wy is an $n \times 1$ vector of observations of the weight of the neighbors influence on the presence or absence of bioenergy facilities. The standard binary response model is then modified by incorporating the weighted dependent variable in to the model. For the probit model

the resulting spatial variant can be expressed as:

$$y^* = \rho W y^* + X\beta + \varepsilon \quad (3-4)$$

Where, y^* is the utility at a location, and ρ is the spatial autoregressive coefficient. The spatial probit can be expressed as:

$$P(y = 1|Wy, X) = G(\rho Wy + X\beta), \text{ and } 0 < G((\rho Wy + X\beta)) < 1 \quad (3-5)$$

The incorporation of the spatial lag into the model allows for the examination of spillovers between regions. Since the dependent variable in this study can only take on two values (i.e. present or absent), the Probit model was chosen for use. While estimating a probit model is fairly straight forward if the error term is normally distributed, using maximum likelihood techniques, the presence of spatial dependence makes estimation extremely hard, if not impossible. LeSage and Pace (2009) proposed the use of Bayesian estimation using a Gibbs sampling approach. This method allows for inferences of both mean and dispersion of all model parameter including spatial lag (Aguilar, 2009).

3.3 ECONOMETRIC DATA

The econometric analysis was performed on county level data for the northeastern United

States (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont and West Virginia) , where each county was identified by its Federal Information Processing code (FIPS). Each 299 counties was defined spatially by using the geographic center point of the county. The latitude and longitude of the center points were then used to define the location of the county. For the econometric model, the dependent variable (Presence of Biomass Facilities) was set to a value of 1 if there were one or more wood based bio-energy facilities located in the county, and 0 otherwise. Wood based bio-energy facility locations in the northeastern U.S. were based on data from Biomass Magazine’s database of biomass energy facilities (Biomass Magazine, 2014). Geo-coded facility locations for all were used for the analysis. Facilities that used Municipal Solid Waste exclusively were excluded from the dataset, to focus on the factors that drive bio-energy facilities that directly use woody biomass resources.

Unemployment rate was used as a proxy for the availability of labor within a county. Previous studies have concluded that the access to labor is one of the major driving forces in the development of an industry (Aguilar, 2009). Additionally, median household income was also included because it is assumed that areas that have a lower median income would be more willing to develop new industries as a way of improving the earnings of the areas inhabitants. Unemployment and median household income data came from the Economic Research Service, U.S. Department of Agriculture (USDA, 2012a).

Timber Product Output U.S. Department of Agriculture (USDA, 2012b) was used as a proxy for both the quantity of forest resources and the quantity of forest products industry present. Higher levels of timber products produced in a region is expected to have a positive

impact on the location of a bio-energy facility in an area for two main reasons. First, in areas of high timber products output there is an already demonstrated availability of the raw resources that can be used directly for feedstock in the form of lower grade/value forest material. Second, high levels of timber products output also mean that there is a functioning forest products industry, which would be a supplier of secondary feedstocks in the form of mill residues.

The additional factors included in the model are electricity prices, road density, political majority and the production of fossil fuels. Electricity price data came from the Energy Information Administration; it is assumed that areas that have high energy cost would be more likely to implement alternative energy (EIA, 2010). Road density is the relative measure of the quantity of road coverage in an area; information for major roads came from the National Atlas.gov and road density was calculated in ESRI ArcGis 10.1 by taking the total length of road divided by the land area in square kilometers to give km/km². The factor of road density is expected to have a positive impact on the probability that a bio-energy facility is present in an area, as ease of delivery of the raw materials should be highly correlated to the amount of roads. Political majority was defined by the results of the 2012 Presidential Election, where 1 was used if the majority of people in a county voted for President Obama and 0 otherwise. The production of fossil fuels in the county were stored as a binary variable in which the variable was coded to 1 if Natural Gas, Petroleum and/or Coal were produced in the county.

Finally, the model includes binary variables for each state that are used to proxy the presence of state level policies and or programs that may either promote or discourage the development of bioenergy facilities in that state. The variable for West Virginia was left out of the model to act as a base case and to avoid multi-colinerarity issues that would have arisen

through the inclusion of the variable. It is assumed that if policies are in place that will attract biomass energy production then the coefficient will be positive, while policies that discourage growth will be negative.

3.4 RESULTS

The results of the spatial autoregressive probit model and the non-spatial probit model are presented in Table 1. Each of the models was estimated through Bayesian Estimation using Markov Chain Monte Carlo simulation with 10,500 draws and a burn in of 500 draws. In the spatial probit model, the variable for Timber Products Output and Political Majority as well as the binary variables for the states of Connecticut, New Hampshire, Massachusetts, Maine, New York and Rhode Island were significant. The signs on the coefficients indicate the type of impact each variable has on the presence or absences of biomass energy facilities. From the coefficients we can see that higher timber output improves the likelihood that a facility will be located in that county. For all the states that were significant the coefficient indicates that there are policy mechanisms in place to entice the development of bioenergy in the area. The model was found to have correctly predicted approximately 93% of the choices.

Table 3-1 Results of the SAR-PROBIT and Non-spatial Probit Models.

Variable	SAR- Probit		Non-Spatial Probit	
	Coefficient	p-Value	Coefficient	p-Value
<i>Constant</i>	-14.3276	0.0385*	-2.8782	0.1374
<i>Unemployment</i>	0.1711	0.2772	0.1143	0.3624
<i>Median Household Income</i>	-0.0037	0.8456	-0.0037	0.8200
<i>Timber Products Output</i>	0.0434	0.0278*	0.0368	0.0335*
<i>Population</i>	0.0056	0.3316	0.0035	0.4782
<i>Road Density</i>	29.8480	0.1282	14.6754	0.3352
<i>Electricity Price</i>	-0.1371	0.2504	-0.0533	0.5358
<i>Fuel Production</i>	-0.5660	0.2084	-0.5982	0.1420
<i>Political Majority</i>	-0.0037	0.0484*	-0.0002	0.7318
<i>CT</i>	13.6573	0.0301*	1.8753	0.0300*
<i>DE</i>	-11.8981	0.4208	-0.2118	0.9344
<i>MA</i>	12.9103	0.0399*	1.1876	0.1565
<i>MD</i>	12.1002	0.0598	0.7798	0.3258
<i>ME</i>	12.9129	0.0423*	1.4974	0.0753
<i>NH</i>	15.6872	0.0110*	3.2733	0.0007*
<i>NJ</i>	2.9595	0.7180	-0.6365	0.7170
<i>NY</i>	12.6740	0.0442*	1.0711	0.1154
<i>PA</i>	12.2502	0.0531	0.9118	0.1611
<i>VT</i>	-1.6316	0.8754	-0.6133	0.7571
<i>RI</i>	14.2698	0.0214*	1.9384	0.0522
<i>ρ</i>	-0.0312	0.7489	-	-

Table 3-2 Direct and Indirect Effect coefficients from SAR-Probit.

	Direct Effects			Indirect Effects		
	Mean	Lower 95%	Upper 95%	Mean	Lower 95%	Upper 95%
Unemployment	0.016	-0.0086	0.04	-1.44E-04	-3.52E-03	0.003
Median HH Inc.	-0.0003	-0.0033	0.003	2.37E-05	-2.26E-04	0
Timber Products	0.0041	0.0014	0.008	-1.05E-04	-8.37E-04	0.001
Population	0.0005	-0.0004	0.001	-9.83E-06	-1.37E-04	0
Road Density	2.7996	-0.3146	5.811	-5.10E-02	-5.95E-01	0.451
Electricity Price	-0.0129	-0.0331	0.004	3.95E-04	-2.01E-03	0.004
Fossil Fuel Prod.	-0.0532	-0.1279	0.014	6.82E-04	-1.01E-02	0.012
Political Majority	-0.0004	-0.0007	0	5.24E-06	-5.87E-05	0
CT	1.306	0.3885	2.381	-1.11E-02	-1.83E-01	0.198
DE	-1.1287	-3.6464	1.118	4.80E-02	-1.81E-01	0.388
MA	1.2361	0.33	2.288	-9.56E-03	-1.75E-01	0.189
MD	1.1589	0.2396	2.217	-5.93E-03	-1.58E-01	0.183
ME	1.2352	0.3259	2.292	-9.89E-03	-1.73E-01	0.187
NH	1.4965	0.5694	2.558	-1.65E-02	-2.18E-01	0.222
NJ	0.2806	-0.8605	1.659	-2.67E-03	-1.17E-01	0.111
NY	1.2133	0.3022	2.259	-8.77E-03	-1.68E-01	0.185
PA	1.173	0.2661	2.213	-7.06E-03	-1.60E-01	0.181
RI	-0.1437	-1.8634	1.395	2.11E-02	-9.17E-02	0.172
VT	1.3632	0.4418	2.415	-1.29E-02	-1.96E-01	0.205

In a probit model, the coefficients cannot be used directly to determine the effects of each variable instead the marginal effects must be used. In the spatial model, the marginal effects are broken into two components: the direct and indirect effects. The direct effects are the effects that a variable has on its own location, while the indirect effects are the effects that a variable has on its neighboring locations. Indirect effects are sometimes called “spillover” effects. Table 2 shows the direct, indirect effect for each variable in the spatial probit model, the total effect can be found by summing the two values. It can be seen that the direct effects are significant for all the variables that are significant in the full model. The significant direct effects are Timber Products Output, Political Majority, the States: Connecticut, Massachusetts, Maine, New

Hampshire, New York and Rhode Island. Examination of the indirect effects shows that none of the indirect effect are significant, suggesting that the effect in a county does not spill over into the neighboring counties. The absence of spillovers is further evidenced by the fact that the spatial parameter ρ was not significant (p-Value=0.7489) indicating that there are not any spatial processes that are influencing the presence or absence of the location of bioenergy facilities in the northeastern United States.

The insignificance of the spatial parameter, led to a non-spatial model being estimated, the results of which are shown in Table 1. In the full model, only Timber Products Output and the state binary variables for Connecticut and New Hampshire were significant while the variables for Maine and Vermont were nearly significant with p-values of 0.0753 and 0.0521, respectively. The percentage of correct predictions for the full non-spatial model was 93%.

With only three significant variables in the model, a backward elimination process was used to eliminate extraneous variables iteratively until only significant variables remained in the model. Upon completion of the backward elimination process, the variables that remained in the model were the variables for Timber Products Output and Fossil Energy production, as well as the binary variable for the state of New Hampshire. The reduced model had an Akaike Information Criterion (AIC) value of 75.71, compared to the AIC value of the full model of 122.86, making the full model only 4.408×10^{-11} times as probable as the reduced model to minimize the information loss (Table 3).

Table 3-3 Variables remaining in the model after completion of the Backward Selection Procedure.

Variable	Coefficient	p-Value
<i>Constant</i>	-1.52956	<2.00E-16
<i>Timber Products Output</i>	0.05174	0.000209
<i>Fossil Fuel Production</i>	-0.74463	0.016276
<i>NH</i>	1.56563	0.000196

The coefficients for the explanatory variables representing Timber Products Output and the state of New Hampshire were both positive. The positive variable for timber output, represents that for each million cubic foot increase in timber output increases the probability that there is an increased chance that there is a bioenergy facility located in the county. This is to be expected, since timber output is being used as a proxy for both the availability of forest resources and the presence of an industry that uses forest resources. Additionally, the presence of a strong forest products industry in the region will, increase the output of mill and forest product residue that can also be used for fuel. Similarly the positive coefficient in the reduced model for the state of New Hampshire, indicates that there is/are state level incentives for developing bioenergy facilities. In fact there is at least one biomass energy facility in 60% of the counties in New Hampshire. While it is not possible to determine what exactly is driving the development, the significance of the variable indicates that there are forces at work that are not present in the other counties. Alternatively, the coefficient for the production of fossil fuel was negative, again this intuitively makes sense. If there is already an energy industry in the county that is based on fossil fuels, the establishment of a bioenergy industry could be viewed as competition and thus policies may exist to protect the established industry.

3.5 DISCUSSION AND CONCLUSIONS

The findings that the locations of wood-based bio-energy facilities do not contain an element of spatial dependence was unexpected. Intuitively, since forested areas are not evenly distributed throughout the northeastern United States, it was assumed that would be intrinsic spatial correlation. The inclusion of timber products output in the final model is evidence that the facilities will be located in areas where forest and forest products are plentiful. Timber products output is basically a proxy for the amount of resource in an area; but additionally, areas that have a strong base in traditional forest products would also have an infrastructure in place for the transportation of the feedstocks. Additional to proximity to the source of feedstock, it is important to identify additional factors that affect why a particular site is selected over another. Through the assumption that firms are free to locate anywhere, that they have all the information needed to make such a decision, and they will try to maximize their utility; it was possible define the relative contributions to utility that each decision variable made by analyzing the location of existing facilities.

Through Bayesian estimation of a spatial autoregressive probit model and also the estimation of a non-spatial probit model, it was found that in the northeastern United States the factors that could be positively affect the utility of an area, were the level of feedstock resource, the absence of competition from traditional fuels and local government policy. Throughout the northeastern United States, there is a large quantity of potential woody biomass energy resources, but the marginal effect for that variable is the lowest in the model increasing the

probability of presence by only 0.6 percent for each million cubic feet of forest products produced. In fact, if there is fossil energy produced in a county there would need to be 13 million more cubic feet of forest products produced in an area than in an area where there is not fossil energy production. However, it is government policy that the results have shown to be the biggest driver of bioenergy development with an absolute magnitude that is 30 times greater than the availability of feedstocks and more than twice as large as the magnitude of the factor for fossil fuel production.

However, there is no evidence that socio-economic factors such as unemployment, median household income, etc. are truly drivers of the development of bioenergy facilities, as suggested by Gan (2006). The results did not point to any factors that would suggest that facilities are being located in areas of high unemployment to spur job growth or in low income levels as a community development and wealth creation tool. Additionally, since the price of energy was not found to be a significant factor, the evidence suggest that energy prices have not yet reached levels where the choice to change to an alternative energy source is being made. Again, this is a discrepancy with one of the cited reasons why bioenergy should be developed (Bridgwater et al., 2002; Caputo et al., 2005; EIA, 2010; Faaij and Domac, 2006; Kaylen et al., 2000; McIlveen-Wright et al., 2001; Tembo et al., 2003; Thek and Obernberger, 2004; Wang et al., 2006). Perhaps rising energy prices will be a driver for bioenergy in the future, but there is no evidence that that is currently the case.

While this study has provided some insight into the factors that are playing a role in where bioenergy development is happening, there are still questions that need to be answered. Additionally, the relatively small sample size of 26 locations containing bioenergy facilities out

of the 299 total locations, it is not possible to account for all possible factors that lead to the siting of bioenergy facilities. This provides a basis for continuing work. These efforts should focus on expanding the current model to provide more detail into the factors that drive these decisions. Additionally, the concept of the use of bio-energy development as a driver for economic development can be explored under a spatial context. The continuation of this research could serve as a platform for further development of bio-energy in the United States.

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4 GIS-BASED SUITABILITY MODELING AND FACILITY LOCATION OPTIMIZATION FOR SITING A COAL-BIOMASS TO LIQUID PLANT

ABSTRACT

The choice of site is of great importance when trying to meet the goal of producing cost-effective biofuels, due to the spatial dispersion of the biofuels and the high proportion of total cost that is incurred by transportation to the processing facility. The proximity to the fuel supply and the resulting transportation cost are the primary concern of the operators of the facilities, although this is not the primary driver that leads to the development of these projects. In order to make these endeavors successful, there must also be buy-in from the local community and its government. Previous studies have found that in addition to the environmental benefits and improved energy security, the impact that the facilities have on the local economy, in terms of job creation, improved industrial competitiveness and regional development are key drivers of bioenergy projects. This study presents a two-stage site selection approach for the siting of woody biomass facilities, which combines multi-criteria analysis with mixed integer linear programming to rank potential development sites. Site suitability was first determined through the use of multi-criteria analysis the used weighting along with fuzzy logic to assign suitability scores, based on economic and environmental attributes. The top 5% of the suitability scores were then used to identify the final candidate locations. Mixed integer linear programming was then used to optimize the facility location based on delivered cost of biomass materials. This approach was then applied to the siting of a Coal/Biomass to liquids plant, and was able to objectively identify the optimal location of the facility.

4.1 INTRODUCTION

Concerns about tightening global supplies of oil, energy security, and climate change have caused a renewed interest in alternative sources of energy. The production of liquid fuels

from coal provides an option of reducing petroleum use in the U.S. transportation sector and enhancing national and economic security by decreasing the nation's reliance on foreign oil (Paul, 2009; Ramage and Katzer, 2009). The technologies of coal-to-liquids (CTL) are well established and have existed for more than 80 years (Van Bibber et al., 2007). Two basic approaches can be used to produce liquid fuels from coal: direct coal liquefaction (DCL) and indirect coal liquefaction (ICL). Today, the world's major CTL production is located in South Africa, based on locally available low cost coal. Coal liquefaction is also given high priority in China. The largest coal producer, Shenhua Group, has launched a DCL plant with a capacity of 24,000 barrels per day. The obvious drawback of CTL technologies is the high carbon footprint of the process (Bartis et al., 2008; Gray et al., 2007). The life-cycle greenhouse-gas (GHG) emissions are about twice those of petroleum-based fuels (Bartis et al., 2008). The ability to capture and store carbon dioxide is very important to producing liquid fuels from coal. If carbon capture and storage (CCS) technologies were employed, a reduction of 5-12% lifecycle GHG emissions could be achieved compared to the average emissions that result from petroleum-derived diesel production (Tarka et al., 2009).

Biomass is the only carbon-based renewable energy resource, which makes it especially valuable for making carbon-bearing liquid transportation fuels. Additionally, the introduction of biomass in a CTL process as coal-biomass to liquids (CBTL) could further reduce GHG emissions (Gray et al., 2007; Paul, 2009; Tarka et al., 2009; Van Bibber et al., 2007). Since the carbon contained in biomass is the result of removing carbon from the atmosphere through the process of photosynthesis, it is considered carbon neutral because it is assumed that the carbon emitted will be used by the plants that are reestablished after the biomass is removed (Gray et al.,

2007). A study from the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) reported that a mixture of 8% biomass and 92% coal (by weight) can produce fuels which have 20% lower life cycle GHG emissions than petroleum-derived diesel fuel (Tarka et al., 2009). The GHG emissions that are associated with biomass in a conversion to liquid fuel process are low and primarily associated with the cultivation, harvest and transport processes (Bartis et al., 2008).

The abundant coal and biomass resources in West Virginia provide a great opportunity for the production of liquid fuels using coal/biomass-to-liquid (CBTL) technologies, but it is imperative that these resources are able to reach the facility at a reasonable price. The cost of feedstocks for energy production is highly location specific (Graham et al., 1997). There are many factors that influence the siting of industrial facilities including economic, environmental and social interests. Each of these individual and possibly conflicting interest must be considered and appropriately balanced during the site selection process. One possible method of balancing these factors is through the use of a multi-criteria decision analysis method. Weighted Linear Combination is the most common procedure used in Multi-Criteria Decision Analysis (MCDA). During this process, each of the factors that is being considered is weighted based on the importance that is placed on the factor. The determination of weights can be done in several ways with the four most popular being ranking, rating, pair-wise comparison and trade-off analysis. Each of these methods has inherent differences based on their ease of use, accuracy, and degree of understanding by the decision makers (Greene et al., 2011). While each of the alternatives has their place, the pairwise comparison technique in the construct of the Analytical Hierarchy Process (AHP), as developed by Sattay (1994), has become the preferred method

based on its stronger theoretical foundation than the alternatives (Greene et al., 2011). AHP has been demonstrated in selecting the location of facilities in a variety of context, including the siting of renewable energy facilities including biomass, solar and wind (Gorsevski et al., 2013; Kaya and Kahraman, 2010; Kühmaier et al., 2014; San Cristóbal, 2011; Uyan, 2013).

In the biofuel sector, one of the largest factors that must be faced, in order to be competitive, is the ability to access the required feedstocks at the lowest possible price (Perlack et al., 2011). This has most often been looked at through optimization modeling. Facility location is just one of the many applications of mathematical optimization modeling. DeMol et al. (1997) used optimization to determine the lowest cost network structure and resulting biomass flows of a multi-source (tree pruning, wood waste, waste paper, and forest thinnings) woody biomass system in the Netherlands. The models were solved by first solving sub-models for each feedstock source and combining the results into a knapsack model to find the optimal set of facility locations and transportation routes. Troncoso and Garrido (2005) used a mixed-integer linear programming (MILP) formulation to simultaneously solve a combined production, facility location and freight distribution problem to minimize transportation costs and ensuring demand is met for the forest products industry in Chile. This methodology could readily be adapted to the bio-energy sector, but may be limited to the size of problems that can feasibly be solved. Ravula et al. (2008) used cotton logistics in Virginia as an analog for biomass transport and optimized the logistics system via the use of greedy algorithms and an implementation of the knapsack problem with travel times. Wu et al. (2012a, 2011, 2010) used a MILP approach to estimate the optimal delivered cost of harvesting and mill residues for the production of liquid fuels in the Central Appalachian region of the United States.

Much of the previous work that deals with facility siting has focused on the price of delivered material and/or the total transportation cost of delivering resources or feedstocks for production (Wu et al. 2011, Zhang et al. 2011). There are few studies that examine the balance between the social and economic factors that interact when a site location is chosen. The determination of site location based on these factors will provide a more accurate estimate of the project feasibility than could be obtained through methods that minimize cost or maximize profit. As part of this project we looked at a region as containing a set of potential facility locations and choosing candidate(s) based on multi-objective decision making methods, taking into account economic, societal and environmental factors. In addition sensitivity analyses are being conducted to examine the uncertainties of biomass availability and cost, plant capacity, capital cost, coal price and the liquid fuel yield on the feedstock price per ton.

The ultimate goal for this study was to optimize siting for a 10,000 barrel per day CBTL facility using a mix of 92% and 8% woody biomass, which minimizes environmental impact and improves the economies for the areas in which they are located.

4.2 METHODS

4.2.1 Study Area

The study was carried out in an 18-county area in southern West Virginia (Figure 1). The study area is geographically located between 37°10' to 38°42' north latitude and 79°58' to 82°40' west longitude. West Virginia (WV) is the nation's second largest coal-producing state, producing more than 120 million metric tons of coal in 2012, about 12% of the U.S. total (EIA,

2013). The majority of the coal in the state is produced in the southern half of the state. Eight counties in the southern central part of the state (Boone, Kanawha, Logan, McDowell, Mercer, Mingo, Raleigh and Wyoming) produce approximately 55% of the state’s coal. Based on the yield of 3bbl of liquids per ton of coal, this 8-county area could support the production of 645,000 bbl. per day.

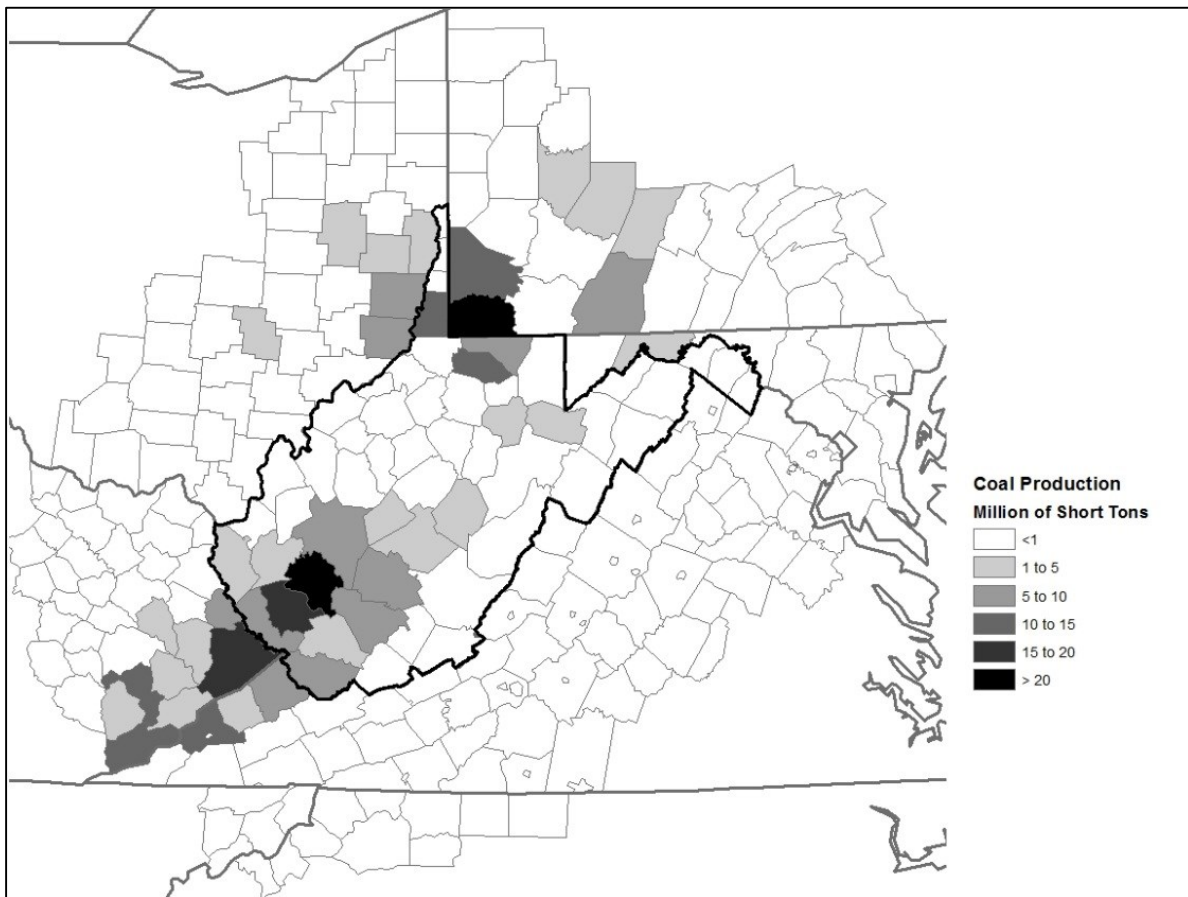


Figure 4-1. Coal production in West Virginia and neighboring areas by county.

In addition to the abundant coal resources, WV is also the third most heavily forested state and the harvesting process annually yields approximately 2.2 million dry Mg (2.4 million dry tons) of woody biomass which can be utilized as feedstock for liquid fuels (Wang et al.,

2006). Logging residue is present and available in each of the WV counties (Figure 2). The amounts shown in Figure 1 were derived using 2006 harvesting data from West Virginia and 2007 TPO (Timber Product Output) data from USDA Forest Service for Kentucky and Virginia. The logging residue densities in the counties of southern West Virginia were based on the surveys completed in recent years to determine logging residue inventory (Grushecky et al., 2007).

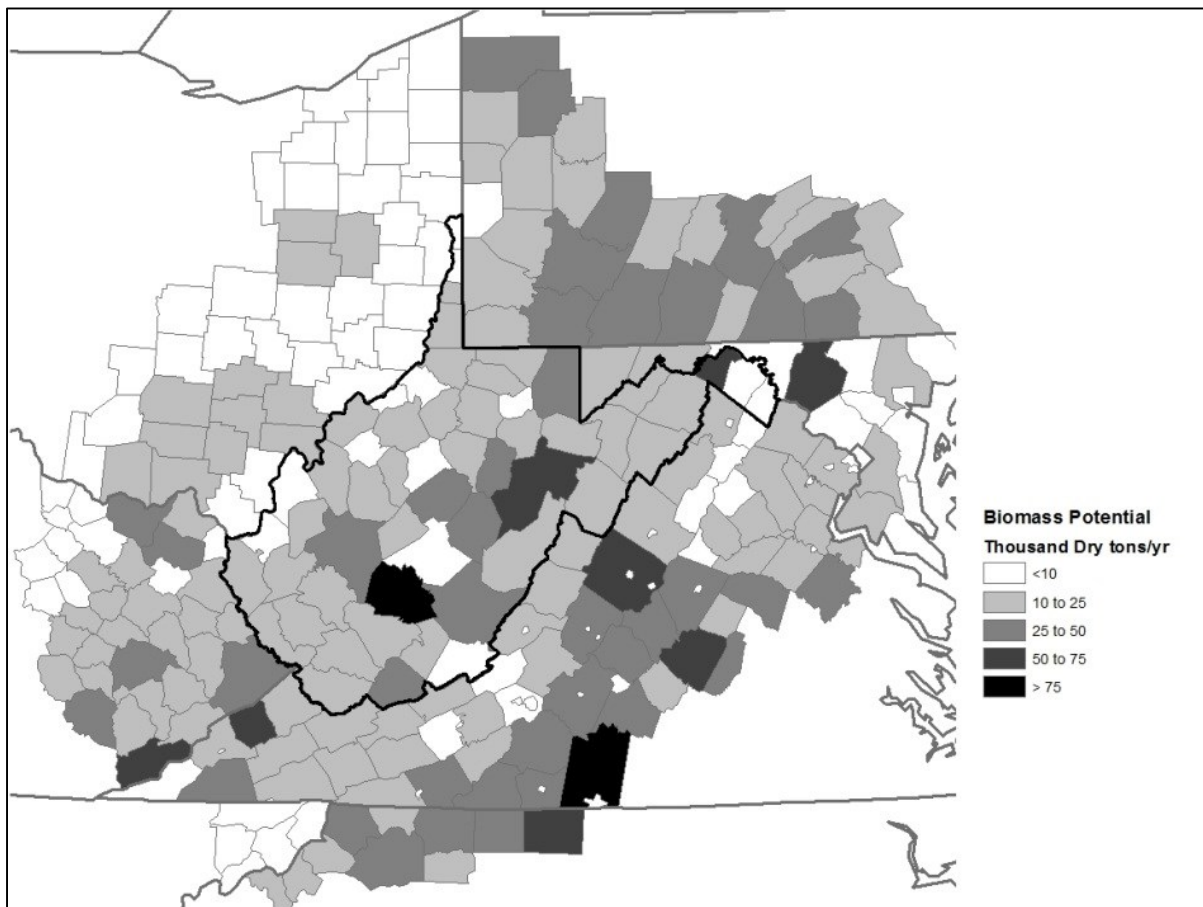


Figure 4-2. Biomass potential in West Virginia and neighboring areas by county.

It was reported that on average there was 23.3 Mg per hectare (10.4 tons per acre) of logging residue left behind after the timber harvest was complete in this region. Multiplying the

harvested acres by the logging residue density for each county in southern West Virginia, the amount of logging residue by county can be determined, which ranged from approximately 19,000 to 71,000 dry tons per year. Considering the terrain constraints and environmental protection regulations, the recovery rate of logging residues was assumed as 65%. The amount of logging residue (in cubic feet) projected were converted to the unit of dry tons by multiplying the density of logging residues 0.616 dry Mg/cubic meter (0.016 dry tons/cubic feet) which was also derived from Grushecky et al. (2006). Mill residue also makes up a significant portion of the woody biomass supply in the region, where there can be as much as 1357.2 dry Mg (1508 dry tons per week produced (USDA, 2012b), and of the residues produced it is estimated that more than 85% of the mill residues are available of use as a bioenergy feedstock.

Aside from the residue that is available from forest operations and industry, there are two other potential sources of woody biomass available in the region; removals from surface mine operations and short rotation woody crops. For example, in West Virginia, surface mining of coal disturbs large areas of forested land annually (Townsend et al., 2009), this produces a fiber resource which has not been highly utilized. The amount of biomass that is potentially available from land clearing prior to surface mining has been studied by Grushecky et al. (2012). They found that an average of 70.1 green Mg per hectare (31.3 green tons per acre) is removed during surface mining operations. While there are currently not large quantities of Short Rotation Woody Crops available in the region, the potential in the future is great. There are an estimated 0.49 million hectares (1.2 million acres) of surface mine sites and 3.64 million hectares (9 million acres) of marginal crop land potentially available in the central Appalachian region. At

current yields this would produce approximately 31 million dry tons of biomass per year, given full site utilization.

4.2.2 First Stage Modeling – Site Suitability Analysis

The first stage of modeling is computing the site suitability index for the study area using a fuzzy logic prediction model. In this model, fuzzy-logic membership functions are used to standardize and transform variables, which are measured at differing scales, to ensure that a positive change in the value of the criterion is associated with a positive change in the suitability index (Wu et al., 2012b).

$$SSI = \sum(f_m w_m) * \prod b_n. \quad (4-1)$$

Where SSI is the site suitability index, f_m is the value of criteria m , w_m is the weight of criteria m and b_n is the criteria score of constraint n . Since the criteria will be measured at different scales, the variables will be transformed and normalized so that a positive change in the variable will be reflected as a positive change in the suitability of the outcome.

The inputs that may be utilized to assess the site suitability of coal-biomass to liquid facilities include general physical properties (i.e. topography, land cover, etc.), proximity to infrastructure (distance from road or rail), access to utilities (distance to electricity, water or natural gas), the availability of raw materials, and environmental factors. In this study, site suitability was evaluated on factors that minimize cost, minimize impact to the environment and maximize benefits to the local economy. In this study, 12 variables were utilized for the evaluation of site suitability (Table 1). The primary focus of the suitability analysis was to

minimize the direct cost for the investors and also the environmental impacts for the surrounding community, while placing facilities in areas that would have the greatest economic impact.

Fuzzy membership functions were constructed for the evaluation criteria, and normalized on the basis of site preference.

Table 4-1. Evaluation variables and criteria for siting a CBTL facility.

<i>Criteria</i>	Evaluation Criteria
<i>Distance from Rail</i>	Euclidian Distance from Rail Line with preference for areas that are closer to rail lines
<i>Distance from Population</i>	Euclidian Distance from the centroid of US Census Designated places with population over 10,000 people, with preference for areas that are further away.
<i>Distance from Fuel Terminals</i>	Network distance from established wholesale fuel terminals with preference for areas that are closer
<i>Biomass availability within 75 Miles</i>	Total Number of Oven Dry Tons available within 75 miles with preference for areas that have higher amounts of Woody Biomass. Must have a minimum of 125,000 odt available.
<i>Unemployment</i>	Unemployment rate as a percentage of the population with preference given to areas with higher unemployment.
<i>Population</i>	Population density of Area: maximum population density 800 persons per square mile and minimum 75 persons per square mile
<i>Distance from Electricity Substation</i>	Euclidean distance from nearest Electricity Substation, with preference given to areas that are closer to substations
<i>Flood Risk</i>	Areas within the flood plain excluded
<i>Direction to nearest population center</i>	Preference given to areas where prevailing wind is away from population center
<i>Land use</i>	Preference given to population center
<i>Ownership</i>	Publicly owned land excluded
<i>Distance to water</i>	Preference given to areas near fresh water source

The weights were determined through the use of the AHP approach, in which each variable was compared to the others. A focus group that included bioenergy experts, engineers, project development experts and environmental experts, were used to rank the criteria. A four-point scale was used to indicate strength of preference in which 1 was used to indicate equality, 3 for slightly prefer, 5 for prefer, and 7 for strongly prefer. A consistency test was performed to assure that the choices were different from random. The criteria for the test was that if the consistency ratio is less than 0.1, the comparisons are consistent and the weight values are valid. For our test the consistency ratio was 0.0264, which confirmed the validity of the weights.

Applying the suitability model through the use of map algebra results in the suitability index, a value from 0 to 1, for each cell in a raster to being defined. The delineation of site suitability on the basis of suitability index can be completed by categorizing them according to threshold values to determine relative suitability.

4.2.3 Second Stage Modeling – Facility Location Optimization

4.2.3.1 Objective function

A MILP model was formulated with the objective of minimizing the cost of delivering woody biomass feedstocks to the gate of a conversion facility. The optimal levels for the decision variables include quantity of feedstock harvested, the quantity of feedstock transported between harvest and conversion sites for each time period, and the location of the conversion facilities. The objective function describes the total costs involved with the harvest, transport and processing of the woody biomass materials that are needed for conversion. The components

that are considered in the function are the harvesting cost, transportation cost, and processing cost. The formulation of the objective function is as follows:

$$\text{Min } Z = \rho + \tau + \mu \quad (4-2)$$

Where Z represents the total cost and ρ, τ and μ represent the harvesting, transportation and processing cost, respectively.

Table 4-2. Harvesting cost components for considered harvesting processes.

	Harvesting Cost (\$/odt)	Stumpage (\$/odt)	Total Cost (\$/odt)
Loose Residue	25.24-29.40	3.00	28.24-31.40
In-Wood Chipping	32.41-40.52	3.00	35.41-43.52

The cost of harvesting the feedstock is made up of two parts: the cost of the actual harvesting operations and payment to the landowner. The cost of the harvesting operations consists of fixed and variable cost of the machinery and operators; including taxes, insurance and fringe benefits. Additionally, there is also an expense of paying the landowner for the right to harvest their material. In this model two harvest methods were considered: Extracting forest material with a grapple skidder and shipping the material in loose form to a centralized chipping facility, extracting forest material with a grapple skidder and chipping on site. The conversion process requires that the chips are bark free, and thus the chipper that is used must have debarking and screening capability. The cost for each harvesting method is presented in Table 2. A grower's payment of \$3 o.d.ton⁻¹ was used in all cases. Also, this model makes the assumption that all feedstocks are accumulated at the centroid of the source county, to ensure that costs were

not underestimated an aggregation cost was added to each of the feedstocks. The total harvesting cost was calculated using the following equation:

$$\sum^M \sum^S \sum^T [HM_{mst} \times (HC_m + itc_{ms})] \quad (4 - 3)$$

Where HM_{mst} is the quantity of material harvested from source location s during period t , HC_m is the harvesting cost associated with a material form and itc_{ms} is the intra-county transport cost for a material m from source s . itc_{ms} is calculated by the following equation:

$$itc_{ms} = 2/3 \sqrt{\frac{Area_s}{\pi}} \times wf \times tr_m \quad (4 - 4)$$

where $Area_s$ is the area of the source county s , wf is a winding factor and tr_m is the transportation cost $\$/\text{ton}^{-1}\text{mile}^{-1}$ for the materials produced.

Transportation of biomass is a major cost element in all energy projects and is of great importance in regards to bioenergy projects, because of the relatively low energy density in comparison to fossil fuels (Saidur et al., 2011). It is estimated that 35% to 50% of the total cost of producing energy from biomass is made up of the delivered cost of the feedstock (Sultana and Kumar, 2011). The cost of transporting biomass feedstocks is dependent on the bulk density the moisture content of the material, and hauling distance. The transportation rates for the woody materials are $\$0.19/\text{Mg}/\text{km}$ ($\$0.27/\text{ton}/\text{mi}$) and $\$0.12/\text{Mg}/\text{km}$ ($\$0.17/\text{ton}/\text{mi}$) for loose residue and chips, respectively.

Transportation costs are calculated with the following equation:

$$\tau = \sum^F \sum^M \sum^S \sum^T \left((TP_{fmst} \times Dist_{fs} \times TC_m) \right) \quad (4 - 5)$$

where TP_{fmst} is the quantity of material m shipped between the source location s and facility f during time period t , $Dist_{fs}$ is the network distance between facility f and source s in miles and TC_m is the transportation cost of material m in \$/Mg/km.

Processing raw material at the facility is also considered part of the feedstock delivery cost, because it is necessary in order to have all the biomass in a uniform format for conversion. The processing of biomass at the facility can reduce the cost since the chippers that are utilized centrally are of very high efficiency and of higher throughput; also when quality of the material is a concern it eliminates the need for debarkers and screens on site. (Tahvanainen and Anttila, 2011). The cost of processing at the facility is calculated with the following equation:

$$\mu = \sum^F \sum^T \left((MP_{mft} \times pvc) + pfc \right) \quad m = residue \quad (4 - 6)$$

where MP_{mft} is the quantity of material processed a facility f during period t , pvc is the variable cost of processing and pfc is the fixed cost of processing.

4.2.3.2 Constraints

The objective function presented in the previous section is subject to a series of material balance, resource availability and operational constraints. The following equations represent the balance of materials flowing in and out of processes. Equations (7) and (8) describe the material

balance for the harvesting operations. Equation (7) ensures that the amount of a material that is produced is less or equal to the available material plus material losses during harvesting.

$$\sum^M HM_{mst} \leq BA_s \times TA_t \quad \forall s, t \quad (4 - 7)$$

Where HM_{mst} is the quantity of material m that is harvested from source s during time period t , BA_s is the total amount of biomass that is available at a source location and TA_t is a temporal availability factor. The temporal availability factor accounts for changes in accessibility due to seasonal weather patterns. Equation (8) ensures that the amount of material that is transported from a harvest site is less than or equal to the material that is harvested from the source.

$$\sum^F TP_{fmst} \leq HM_{mst} \quad \forall m, s, t \quad (4 - 8)$$

Equation (9) states that the quantity of material that is processed at a facility (MP_{mft}) cannot exceed that quantity of material that has been transported to the facility (TP_{fmst}) for all time periods and facilities.

$$MP_{mft} \leq \sum^S TP_{fmst} \quad \forall f, t \quad m = residue \quad (4 - 9)$$

Equation (10) is the constraint on the feedstock that is required for the plant to operate. The constraint requires the total biomass of both chips and residues that are

transported to the facility and the material that is processed at the site equates the demand for the time period if the facility is open.

$$\sum TP_{fmst|m=chip} + MP_{mft} = FR_f \times y_f \quad \forall f, t \quad (4 - 10)$$

4.3 RESULTS AND DISCUSSION

4.3.1 Analysis Scenario

4.3.2 Weight Preference

A pairwise comparison matrix was created to reflect the preference of the proposed evaluation criteria. The eigenvector method was used to derive both the weights and the test for inconsistency between responses as proposed by Saaty (1994). The consistency ratio value (0.026) for the responses was lower than 0.1, validating that the responses were consistent among respondents. The distance from rail (weight=.2257) was judged to be the most important factor, since requirement for coal is of such importance to the process and rail is the primary and most cost effective way that coal is transported. Having a facility that is capable of taking rail delivery of coal shipments will reduce costs and enhance the profitability of the facility. The factors availability of biomass and distance to water were seen as slightly less important than access to rail, but equal to each other in weight (weight=.1698). The pairwise comparison matrix with weights for all the factors in the fuzzy logic prediction model can be seen in Table 4.

Table 4-3. Pairwise comparison matrix and relative weights of fuzzy logic model variables.

	Rail	Biomass	Water	Electric	Demand	Flood	LandUse	Pop	Own	Dist to Pop	Dir to Pop	Unemp.	Weight
Rail	1	1	1	3	5	5	5	7	7	7	7	7	0.226
	0.215	0.172	0.172	0.292	0.278	0.278	0.278	0.250	0.250	0.175	0.175	0.175	
Biomass	1	1	1	1	3	3	3	5	5	7	7	7	0.170
	0.215	0.172	0.172	0.097	0.167	0.167	0.167	0.179	0.179	0.175	0.175	0.175	
Water	1	1	1	1	3	3	3	5	5	7	7	7	0.170
	0.215	0.172	0.172	0.097	0.167	0.167	0.167	0.179	0.179	0.175	0.175	0.175	
Electric	0.333	1	1	1	1	1	1	3	3	5	5	5	0.106
	0.072	0.172	0.172	0.097	0.056	0.056	0.056	0.107	0.107	0.125	0.125	0.125	
Demand	0.2	0.333	0.333	1	1	1	1	1	1	3	3	3	0.060
	0.043	0.057	0.057	0.097	0.056	0.056	0.056	0.036	0.036	0.075	0.075	0.075	
Flood	0.2	0.333	0.333	1	1	1	1	1	1	3	3	3	0.060
	0.043	0.057	0.057	0.097	0.056	0.056	0.056	0.036	0.036	0.075	0.075	0.075	
LandUse	0.2	0.333	0.333	1	1	1	1	1	1	3	3	3	0.060
	0.043	0.057	0.057	0.097	0.056	0.056	0.056	0.036	0.036	0.075	0.075	0.075	
Pop	0.143	0.2	0.2	0.333	1	1	1	1	1	1	1	1	0.037
	0.031	0.034	0.034	0.032	0.056	0.056	0.056	0.036	0.036	0.025	0.025	0.025	
Own	0.143	0.2	0.2	0.333	1	1	1	1	1	1	1	1	0.037
	0.031	0.034	0.034	0.032	0.056	0.056	0.056	0.036	0.036	0.025	0.025	0.025	
Dist to Pop	0.143	0.143	0.143	0.2	0.333	0.333	0.333	1	1	1	1	1	0.025
	0.031	0.025	0.025	0.019	0.019	0.019	0.019	0.036	0.036	0.025	0.025	0.025	
Dir to Pop	0.143	0.143	0.143	0.2	0.333	0.333	0.333	1	1	1	1	1	0.025
	0.031	0.025	0.025	0.019	0.019	0.019	0.019	0.036	0.036	0.025	0.025	0.025	
Unemp.	0.143	0.143	0.143	0.2	0.333	0.333	0.333	1	1	1	1	1	0.025
	0.031	0.025	0.025	0.019	0.019	0.019	0.019	0.036	0.036	0.025	0.025	0.025	

4.3.3 Site Suitability

Using ArcGIS 10.2, the SSI for each cell in the study area was computed based on Equation 1. The suitability ranged from 0 to 0.7837. The top 5% of suitability indices were selected as areas that were considered suitable for siting a CBTL facility. The range of suitability indices for the selected area ranged from .7683 to 7837. The location of suitable areas can be seen in figure 3.



Figure 4-3. Location of calculated suitable areas.

Each of the sites had all of the necessary requirements for a CBTL facility, including rail access, a sufficient water supply, and close access to three phase electricity. Additionally, industrial areas were added to the analysis. Within the study area there were 94 industrial sites. Of the industrial sites within the study area there were only nine that lay within the areas found suitable for building a CBTL facility. The nine sites that were within the suitable areas were selected a candidate locations for use in the facility location model. The location of the candidate facilities in the study area are shown in Figure 4 and the suitability scores for each location are presented in Table 5.

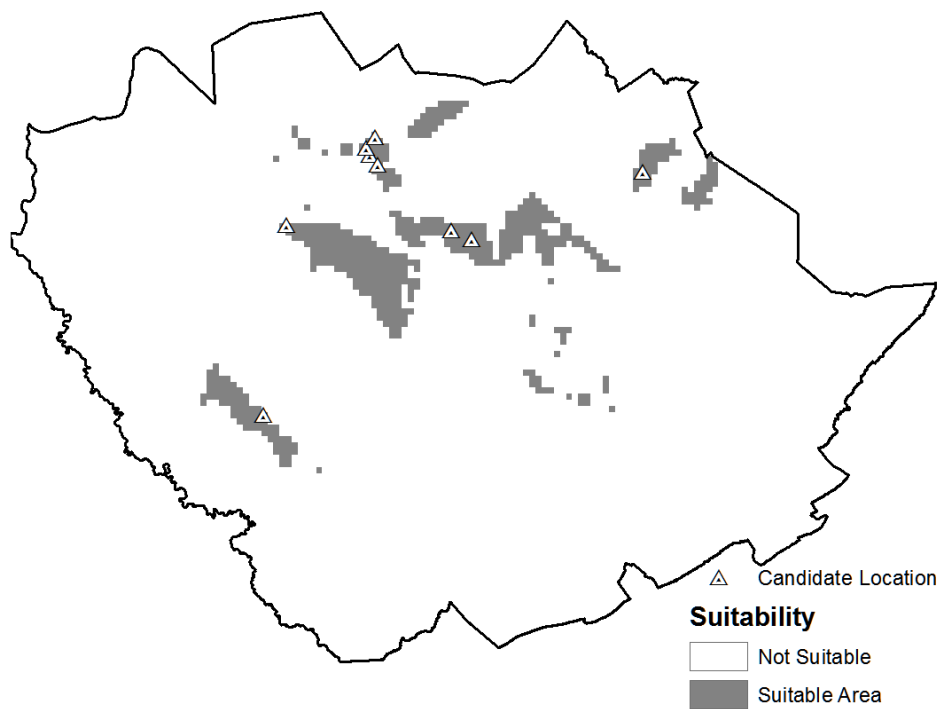


Figure 4-4. Location of selected candidate facilities based on suitability analysis.

Table 4-4. Suitability indices for selected candidate sites.

Site	Nearest City	Suitability Score
North Gate	Charleston	0.7790
Longacre Bottom	Smithers	0.7780
Ronald Lane	Charleston	0.7768
Handley	Handley	0.7748
McDonald	Taplin	0.7744
Wash Branch	Danville	0.7743
Glade Creek	Summersville	0.7728
Mink Shoals	Charleston	0.7722
Washington Heights	Charleston	0.7708

4.3.4 Ranking of Sites

The nine sites that were identified during the suitability analysis were used as inputs for facilities in the facility-location model. The model was then used to evaluate the cost of delivering biomass to each facility. The base scenario used a facility demand of 10800 dry Mg per year, or 10,000 odt per period based on a 10,000 bbl per day facility using 92% coal and 8% biomass by weight. Each site was compared on the total delivered cost per ton of biomass, it was assumed that the quantity of coal that would be necessary would not be a limiting factor in production. Glade Creek was found to have the lowest delivered cost for biomass at \$36.92 per odt, nearly three dollars per ton less than the next closest site, Handley, with a cost of \$39.78 per odt (Table 6). The site that had the highest delivered cost was the Longacre Bottom site, with a delivered cost of \$47.70 per odt. The site with the highest suitability index, North Gate, ended up ranking fourth out of nine, with a delivered cost of \$40.27 per odt.

Table 4-5. Delivered cost and ranking of candidate sites.

Site	Delivered Cost	Rank
Glade Creek	36.92	1
Handley	39.78	2
Mink Shoals	39.88	3
North Gate	40.27	4
Washington Heights	40.3	5
Ronald Lane	40.92	6
Wash Branch	41.98	7
McDonald	42.47	8
Longacre Bottom	47.7	9

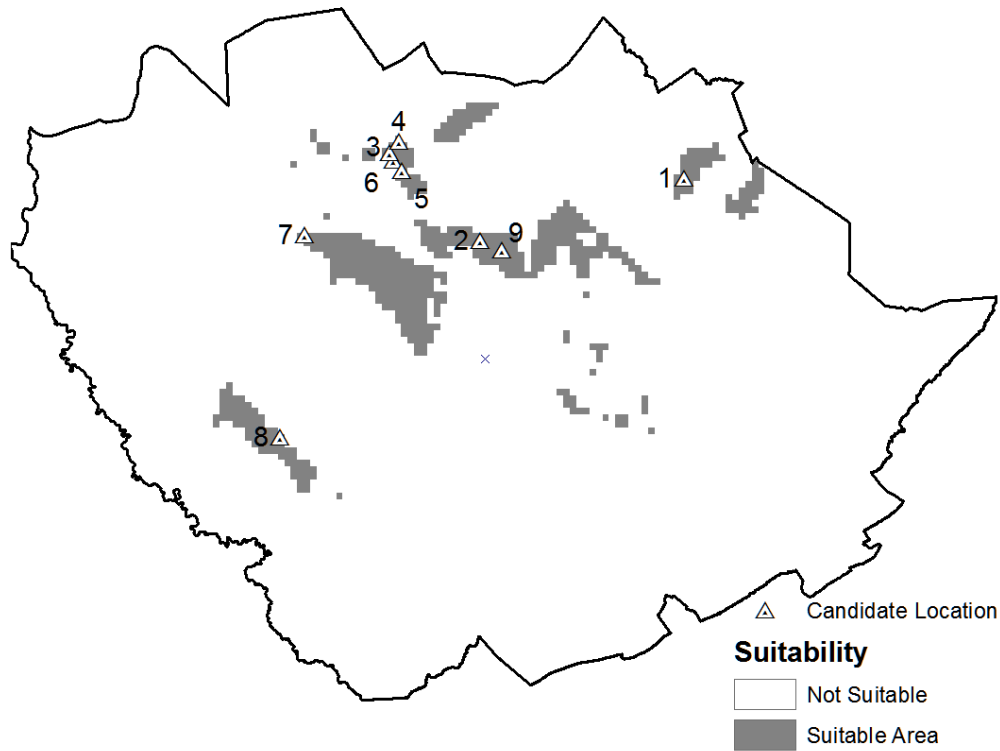


Figure 4-5. Locations and ranking of candidate sites for a CBTL facility.

4.3.5 Factors Contributing to Site Ranking

The percentage of feedstock demand that must be met using material that comes from in-woods chipping operations had a negative effect on where the sites ranked. Of the nine sites, only the three lowest ranking sites used in-woods chipped material to meet demand. The lowest ranked site, Longacre Bottom, used 97.6% in-woods chipped material to meet demand.

Similarly the next two lowest ranked sites McDonald and Wash Branch, met their demand with 17% and 16.3% in-woods chipped material, respectively. The use of in-wood chipped material raises harvesting cost, and indicates that the material is located at a distance that is too far to transport in loose form economically. The average distance that the three in-woods chip using

facilities transported was over 80 km (50 miles), while the facilities that transported residue and processed at the facility had an average transport distance of 44.03 km (27.36 miles). While each site selected had sufficient volumes of woody biomass within an assumed economic transport distance of 120 km (75 miles), it is clear that the highest ranked sites were placed amid the resource and not merely close to the resource, allowing them to have an advantage in terms of cost of feedstock.

4.4 DISCUSSION AND CONCLUSIONS

This study has presented a methodology to identify and select the locations for coal/biomass to liquid facilities using GIS based suitability analysis and facility-location optimization. The suitability analysis allows for the identification of areas that meet a minimum set of criteria for varying and sometimes disparate objectives. We evaluated that sites based on factors that contribute to the cost for the investors, environmental and potential economic impacts. The suitability index for each cell (size) in a raster that covered the study area was calculated using a fuzzy-logic prediction model that incorporated AHP results. Industrial sites that were contained within the defined suitable areas were chosen a candidate sites. The identification of suitable sites incorporated a considerable amount of economic and environmental data, with decision rules about which factors are necessary when siting a CBTL facility. While this study included all the basic factors necessary for evaluation, there are a myriad of factors that could be included in the site selection process to refine site selection further.

The proposed approach was applied in an 18 county area in southern West Virginia, and was successful in taking spatial data of differing scales and subject matter and integrating it together to identify and rank potential sites for CBTL facilities. In addition to selecting the site the inclusion of optimization modeling allows for the examination of factors that contribute to the rank and provides a basis for the investors for determining costs. The results can be utilized as inputs into financial models as the planning process continues.

Future research will be needed to evaluate the economics of siting plants in the areas that have been identified. The study area has a demonstrated high level of the resources that are needed. The economic impacts (i.e. job growth, tax revenue, and rural development) can be evaluated through the use of a variety of economic analysis tools such as input-output analysis or computable general equilibrium modeling. The environmental impacts can be evaluated further using Life Cycle Analysis. The Life Cycle Analysis will provide baseline estimates of the impacts to soil, water and air and provide information on areas where improvement may be possible.

This study provide a framework that can be used to screen and ultimately rank potential areas for development and siting of CBTL facilities. Additionally, these methods could be extended into the siting of a variety of types of facilities that have the delivery of feedstocks as a major cost component. The limitations of this method lay in the defining of the criteria weights and the inherent subjectivity contained within. It is possible to vary the weighting schemes, and compare the results to find areas of overlap.

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**5 DEVELOPMENT OF A HARVEST SIMULATION MODEL TO
DETERMINE ECONOMIC AVAILABILITY OF WOODY BIOMASS
FEEDSTOCK FOR BIOENERGY PRODUCTION**

ABSTRACT

A simulation model was developed to assess the locally available quantities and prices for biomass feedstocks. The simulation uses machine tractability in conjunction with graph theory to assess machine productivity and harvesting cost. Terrain information from digital elevation models along with land cover and forest inventory data were used to create weighted graphs of forest stands. The weighted graphs were analyzed using Dijkstra's algorithm to find the shortest path between each forest supply point and the landing. The paths were then analyzed for machine tractability to determine the quantity of material that can be transported from each supply point to the landing. The model was then applied to a demonstration project in which a 10,000 bbl per day Coal/Biomass to Liquid plant is being used to examine if there are sufficient feedstocks available to warrant the project. It was found that within the proposed three county procurement area that there were approximately 34% less material available than was assumed to be available from large scale feedstock data. Also, the simulation model was able to determine that the total feedstock requirement could be met at a price of \$66 per dry Mg.

5.1 INTRODUCTION

The social and political environment in the United States has led to expanded interest in the role of biomass energy into the future. The increased frequency of extreme weather events, which have resulted in billions of dollars of economic losses, in the United States, has been suggested to be a result of global climate change (Banholzer et al., 2014), which has led to policy such as the Renewable Fuel Standard as well as numerous tax incentives for the production of renewable energy. Additionally, many states have followed the federal government's lead, and have adopted Renewable Portfolio Standards (RPS) in efforts to reduce

the emission of greenhouse gasses in to the atmosphere, and slow the rate of climate change (US EPA,2010).

Biomass is being considered for the production of energy in areas where the use of wind and solar is not feasible. Biomass for bioproducts and bioenergy can be sourced from forests, agricultural crops, various residue streams, as well as dedicated woody and herbaceous crops (USDOE 2011). Woody biomass feedstocks have several advantages over agricultural sources, especially in the northeastern US (NE) where forests make up 67.4% of the total land area (Smith 2009) and agricultural production has been in a 20-year decline. Woody biomass is available year-round from multiple sources, so end users are not dependent on a single source of material; this ensures a consistent feedstock supply, reduces the risk of dramatic price fluctuations, and eliminates the needs for complicated and expensive long-term storage of material. As perennial cropping systems, both forests and short rotation woody crops (SRWC), like willow and hybrid poplar, produce a number of environmental benefits beyond a renewable source of biomass and are less prone to fluctuations in yield due to abnormal weather patterns or pest and disease outbreaks than annual crops.

The Northeast already has a wealth of existing feedstocks and the potential to increase supplies in the future. There are currently between 1.35 and 25.64 million dry tons of woody biomass available per year from integrated forest operations in the northeast at a price between \$60 and \$90 per dry ton (Perlack et al., 2011). It is also estimated that the region will be able to sustainably produce between 80.7 and 141.5 million dry tons of biomass per year, in the form of Short Rotation Woody Crops and energy grasses, by the year 2030 (Perlack et al., 2011). The availability of these resources provide a competitive advantage for economic development

(Marcouiller et al., 2004). Biomass harvesting, transportation, and processing are labor intensive, and the spatial distribution and relatively low bulk density limit the economical transportation distance of these materials; leading to markets that are distributed throughout a region.

In the northeastern United States, the primary method of extraction of forest residues would be through the use of a skidder or a forwarder (Li et al., 2006; Grushecky et al., 2007). The residues can then either loaded directly to a truck or comminuted, in order to improve transportation and handling characteristics, using in-woods chipping. The transportation of loose material is preferable when the material is large enough to meet the weight capacity before exceeding the dimensional limits. If this criterion is met, or the transportation distances are short (less than 35 miles), it is preferable to utilize centralized chipping, due to the centralized chipper's increased efficiency and lower per unit cost (Rauch and Gronalt, 2010; Tahvanainen and Anttila, 2011). In cases where full loads cannot be obtained with the raw material it is preferable to comminute the material to increase the bulk density. Increase of the bulk density improves the transportation characteristics, transforming the material into a form that can transported economically (Tom L. Richard, 2010). Both types of operations require large capital investments.

Traditionally, woody biomass has been considered a low value product, and consequently little emphasis has been placed on the efficient harvest, extraction and transport of this potentially valuable material. As energy markets develop, value will be added to these products and lead to increased harvest and collection (Becker et al., 2009). Even with the increases in market value associated with increased demand, harvesting and collection cost may be a limiting factor in the true availability of woody biomass feedstock. While collection and primary

transport of logging residues can be completed using current timber harvesting systems, their efficiency is dependent on machine payloads; the terrain in which they are working; and the spatial distribution of the residue. Each one of these factors will affect the cost of the feedstock. In addition, transportation of woody biomass is also a challenge due to the material's low bulk density, making it difficult to maximize allowable load limits (Spinelli et al., 2007).

The economic availability of biomass feedstocks is a topic that has been well developed in the literature. There are several resource assessments that have been developed on a national scale, two examples are: (Gan and Smith, 2006; Perlack et al., 2011). Perhaps the most cited assessment is the U.S. Billion-Ton Update: Biomass Supply for a Biofuels Industry by (Perlack et al., 2011). In this report, an assessment is made for the nation, at a county level scale, on the availability of biomass feedstocks by price. While this report provides a good baseline for biomass availability, the assumptions that were made result in a lack of detail. Additionally, there have been several studies that examine the extraction cost of feedstocks at the compartment or individual stand level (Yoshioka et al., 2011; Zambelli et al., 2012).

The capacity of an extraction machine is highly correlated to the topography in which the harvesting operations are taking place (Greulich et al., 1999). The ground conditions of a specific site can limit the movement of the machines and reduce effective payloads, to the point where the machine is rendered ineffective (Spong, 2001). The examination and modeling of machine tractability has been studied in forest operations since the mid 1950's. Herrick (1955) published "Tractive effort required to skid hardwood logs". In 1977, Perumpral et al. (year) published mathematical models that predicted the skidding forces on logs. In the early 1980's Olsen et al. (1983) published "Predicting Skidder Productivity: A Mobility Model", in effort to

have a computer program that would be able to predict the production that could be expected in ground based logging operations, based on terrain information. Additionally, Hassler et al. (1983) produced SKIDLOG, an interactive computer simulation model that was intended to evaluate skidder productivity under various ground conditions.

The use of machine capability will allow for the estimation of the productivity of forestry operations at a localized level. Traditionally, biomass availability assessments have been carried out on a large scale and have not been able to provide detailed information to perspective bioenergy developers. The objectives of this study were to demonstrate a method in which simulation can be used to assess the local economic availability of forest biomass for use in the development of bioenergy projects.

5.2 DATA AND METHODS

5.2.1 Data

Three types of spatial data were utilized in this study: land cover, elevation and county boundaries. The land cover data used was the 2006 National Land Cover Database provided by the Multi-Resolution Land Characteristics Consortium, of the US Department of the Interior and the U.S. Geological Survey (USGS). The land cover data were at a 30 meter spatial resolution, and was the most current available at the time of this study, and they were clipped to the boundary of the state of West Virginia to minimize file size and facilitate use. Elevation data came from the 30 meter National Elevation Dataset from the USGS, a UTM NAD83, 1:24000 scale subset of the data were acquired from the West Virginia GIS Technical Center. The county boundary data, were also acquired from the West Virginia GIS Technical center. The county

boundaries were at a spatial scale of 1:24000 and were projected to a UTM NAD83 (Zone 17) projection. In addition to the spatial data, forest inventory data for annual growth and above ground biomass were used and acquired from the U.S. Forest Service, through their Forest Inventory Data Online (FIDO) data retrieval interface.

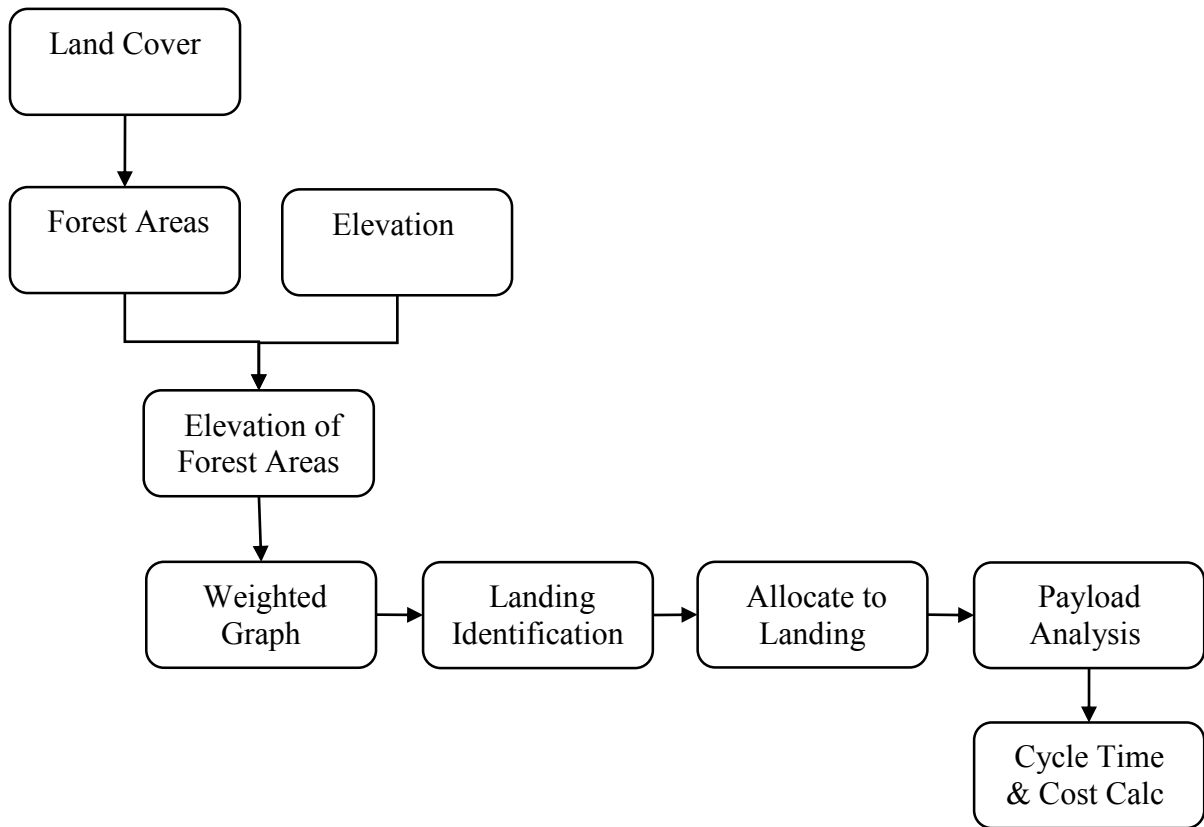


Figure 5-1 Flow chart of modeling process.

5.2.2 Extraction of Forest Areas

The first step of the process was to extract the forest areas from the land cover raster. The land use codes 41, 42 and 43 in the National Land Cover Database correspond to Deciduous Forest, Evergreen Forest and Mixed Forest respectively. The map algebra tool, in ARCGIS 10.2,

was used to reclassify the land cover raster. A binary classification system was used in which forest area was set to a value of 1 and all other land uses were set to 0. After classification, the raster, that now represented the forest area in the state, was converted to polygons that represented the individual forest areas, and non-forest areas. The non-forest areas were removed from the dataset, to leave only the polygons that represented the forest area of the state. The statewide forest polygon shapefile was then clipped to the boundary of each county to establish a county-level coverage of forestland boundaries that will be used to extract the elevation data for each forest area in a county.

5.2.3 Extraction of Forest Elevation Data

The analysis of machine working payloads requires information about the terrain in which the machine is being utilized. The only elevation information that was required, was the elevations for the stands themselves. To that end, the elevation raster was clipped to each individual forested area. Before the elevation raster was clipped, the forest area shapefiles were cleaned of any areas that were below a threshold size that would make it economically infeasible to harvest. In this study, the minimum threshold was 8.092 ha. (20 ac.). After the clipping, there was an individual elevation raster for each forest area. Each raster was processed using the Geospatial Data Abstraction Library(GDAL) and Raster packages in R 3.1.1 to obtain arrays of X, Y and Z values for each forested area.

5.2.4 Creation of Weighted Graphs

The graph theory has been widely used to solve a host of problems in the area of forest networks (Sakurai et al., 2002; Stükelberger, 2008). A graph is simply a set of nodes or points that are connected with edges or links that connect two of the nodes. A weighted graph is

essentially the same but the edges are weighted or have a cost associated with the travel between two nodes. In general, graphs are used to facilitate finding the shortest or least cost path between two locations on the graph. For this project, the nodes of the graph are represented by the arrays of X, Y, Z coordinates, which is the center of each cell in the forest area level elevation rasters.

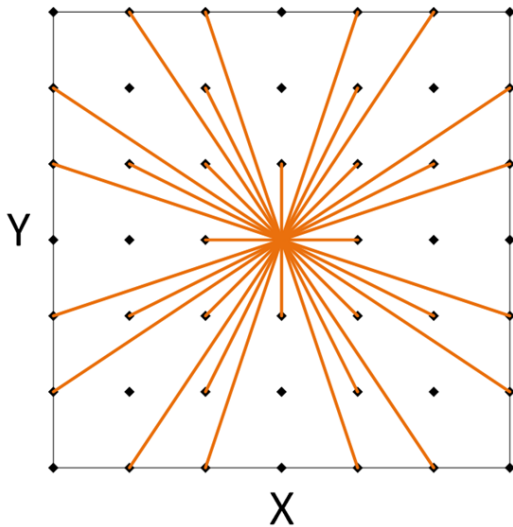


Figure 5-2 Graphic representation of node connection pattern.

The links or edges are created based on each point having a maximum of 32 connections (Figure 5-1). The slope distance between nodes was recorded as a weight parameter for each link or arc (Equation 5-1).

$$SD = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \quad (5-1)$$

Where:

SD=Slope Distance

Δx =change in x direction (longitude)

Δy =change in y direction (latitude)

Δz =change in z direction (elevation)

In an attempt to reduce the number of links that would need to be visited during the search process and to ensure that the average gradient of the extraction route would be less than 20% slope, links would only be added to the graph if the slope was less than or equal to 20%. In addition to the initial weights, for the links added to the graph, a slope penalty was implemented for slopes over 5% to ensure that there was a preference for flatter terrain.

5.2.5 Identifications of Landing Locations

The log landing serves as the hub of harvesting activity, it is in this location that material is stored, process and made ready for transport. In general, landings are located in areas in which the terrain is gentle and provides a staging area in which the processing machines can be stationed and work efficiently. To identify candidate landing areas within the forest areas, each graph was searched to find areas of approximately of 0.10 ha (0.25 ac) in size with a slope of less than 5%, in accordance with the timber harvesting Best Management Practices of West Virginia (WV Div. of Forestry, 2014). The search algorithm selected a point and checked the slope in each of the cardinal directions and on each diagonal. If all slopes were less than or equal to 5%, the node was added to a candidate list. After the entire graph was searched and all potential landings were identified, the candidate list was used to identify which of the landing candidates would be used in the distance analysis. This step was necessary, since many times there were several candidates that were spatially close together. Candidate landings were selected in the order in which they were placed in the candidacy list, and the selected candidate

was placed in the final landing list. The candidate list was searched to find all the candidates that were within a minimum distance threshold, and any candidate that fell within the threshold was deleted from the list. For this study the threshold that was used was 630 meters, equates roughly to the average economic travel distance in the region (cite). The resulting list was then used as landing sites for the payload analysis.

5.2.6 Allocation of Nodes to Landings and Determining Travel Distance

The irregularity of the shape of the forest area boundaries as well as the heterogeneity of topography that was found in the forest areas did not allow for the arbitrary assignment of graph nodes to landings based on Euclidean distance, instead nodes were allocated to landings based on the least cost of extractions. The least cost extraction distance was calculated for each node to each of the final landings using Dijkstra's algorithm (Dijkstra, 1959), with each node being allocated to at most one landing. If the node attribute for landing allocation was null, which specifies if the node had not been allocated to a landing, and the distance found was less than an arbitrarily large distance of 100,000 m, then the node was allocated to the current landing, and the distance was stored as an attribute of the node. If the allocated landing property was not null, indicating the node had been previously allocated to a landing, the calculated distance was compared to the current distance attribute. If the current calculated distance was less than the value that is currently stored, the current landing replaces the stored landing in the allocated landing attribute and the calculated distance is stored as the distance to the landing. This process is continued until all nodes are either allocated to a landing or it is determined that a point is not connected to any of the landing locations in the graph.

5.2.7 Determination of Payload to the Landing

The payload that an extraction machine can take to the landing is a combination of the tractive force of the machine and the resistive force of gravity and the load that it is carrying (Hassler et al., 1983). The formula for calculating payload is given by equation 5-2.

$$Payload = \frac{[(2 \times Force) - (0.4 \times wt \times \cos \theta) - (2 \times wt \times \sin \theta)]}{1.05 \cos \theta + 2 \sin \theta} \quad (5 - 2)$$

Where:

Force = Drawbar force of the machine

wt= the weight of the machine

θ = the angle of the slope in degrees

The drawbar force of the machine is variable and depends on both horsepower and speed. Figure 4-2 gives a graphical representation of the relationship between speed and pulling capacity of a machine. The calculation for drawbar pull in that was used for this study was based on a Caterpillar 525 Skidder (Caterpillar, Inc, 1998) and the formula is given by equation 5-3

$$Force(Mg) = (0.8971e^{-0.262 Speed}) \times 20 \quad (5 - 3)$$

The angle of the slope (θ) is found by taking the arctangent of the slope between the two terrain points. During the landing allocation and distance calculation process the preceding node on the path is stored as an attribute for the node. Both the current node and preceding node have X, Y, and Z coordinates stored as attributes, which allows for the slope to be calculated between

the nodes. The inverse slope must be used, because the direction of travel is opposite the direction of analysis. The slope between the nodes is calculated using formula 5-4.

$$Slope = -\frac{Z_{pred}-Z_{curr}}{\sqrt{(X_{pred}-X_{curr})^2+(Y_{pred}-Y_{curr})^2}} \quad (5 - 4)$$

The payload formula (equation 5-2) provides the amount of payload that can be transported between two nodes, but it is not always possible to bring the full load from a node to the landing due to a payload limitation at an intermediate node on the path. Points that limit the payload are termed limiting points and their identification is a tracing process that must proceed from the landing to the node being analyzed. The identification of the limiting points in the path starts with the connection between the landing and the first connected node. The payload for that link is compared to the maximum safe working load, if the calculated payload is less than the max payload then the calculated payload becomes the maximum load that can be transported past that node. The process continues iteratively until all points have a limited payload attribute or a point is identified, in which the limiting payload is zero.

5.2.8 Calculation of Cycle Time and Cost per Ton

The determination of the break-even cost per Mg for each node, begins with a determination of cycle time. Cycle time is essentially a function of distance and speed with the addition of non-travel working time and delays. The formula for estimating the cycle time in seconds is given by equation 5-5.

$$Cycle\ time = (Dist \div Unloaded\ Speed) + (Dist \div Loaded\ Speed) + NonTravel \quad (5 - 5)$$

Where:

Cycle time= the time to complete one productive cycle in seconds

Dist= the travel distance from the landing to the current node in meters

Unloaded speed= Machine speed when unloaded in m/s

Loaded Speed= Machine speed when loaded in m/s

NonTravel= Time taken for non-travel work and delay

After cycle time in seconds is determined the cost per cycle is determined through equation 5-6

$$\text{Cost per cycle} = (\text{Cycle time} \div 3600) * \text{HMR} \quad (5 - 6)$$

Where:

Cost per cycle= the cost in dollars for a productive cycle

Cycle time= the time to complete a cycle in seconds

HMR= the hourly cost of the machine in dollars per hour

Finally, cost per Mg is determined by equation 5-7

$$\text{Cost per Mg} = \text{Cost per cycle} \div \text{payload} \quad (5 - 7)$$

Where:

Cost per Mg= the cost in dollars of a Mg of biomass

Cost per cycle=the cost per cycle in dollars

payload= the payload to the landing in Mg

5.3 APPLICATION

The model and analysis procedures developed were utilized to examine the economic availability of biomass feedstocks for a proposed 10,000 bbl per day Coal/Biomass to Liquids (CBTL) facility to be sited near Summersville, WV. The selection of this site is an extension of the analysis completed in Chapter 4, and is the site selected as result of the preliminary facility siting analysis. It is assumed that the facility will use 92% coal and 8% woody biomass as feedstocks for production, which was also used for the previous study, equating to an annual biomass demand of approximately 109,000 dry Mg. During the previous study, the areas were identified that will serve as supply areas for the plant. For this study the same procurement area was assumed and included the three West Virginia counties of Clay, Fayette, and Nicholas (Figure 5-3).

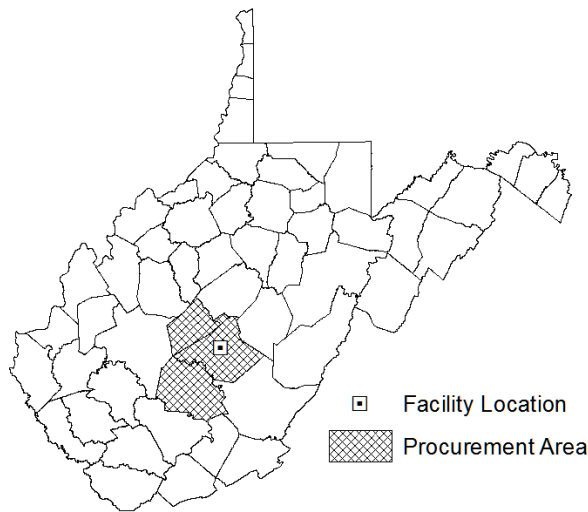


Figure 5-3 Proposed CBTL Plant Location and Assumed Procurement Area.

All harvesting was assumed to be completed using an integrated harvest in which biomass is harvested in conjunction with the removal of saw timber, to improve productivity and reduce costs (Grushecky et al., 2007; Perlack et al., 2011). The machines that were used in the harvest of the material consisted of a feller-buncher and grapple skidder system, which is a common harvesting system in the region. It was assumed that the feller-buncher would cost \$110.54 per scheduled machine hour and that the grapple skidder would cost \$91.32 per scheduled machine hour. These cost were taken from Li et al. (2006) and adjusted for inflation and moisture content. This study also assumed that there are enough harvesting contractors within the area to be able to satisfy the demand of the CBTL facility and that all biomass is available to the market. Also to ensure that feedstock is available into the future, a limit was placed on the quantity of material that can be harvested. The total harvest was limited to the average annual growth of forests or 2.4% of the total volume.

5.4 RESULTS & DISCUSSION

5.4.1 Biomass Availability

The three counties in the procurement area were analyzed independently to determine the cost of the biomass to the landing. The number of individual forested areas that were examined in each county ranged from 97 in Clay County to 255 in Nicholas County. The land area of the contiguous forested areas ranged from 8.09 ha (20 ac) to 17,587 ha (43,411 ac). After completion of the analysis it was found that the only 68%, 78% and 79% of the forested areas were able to be harvested in Clay, Fayette and Nicholas, respectively. The remaining forested areas that could be harvested in accordance with the slope requirements, equated to 40%

of the forest land area in Clay, 33% of the forest land in Fayette and 39% of the forest land in Nicholas.

The analysis for each county yielded both the quantity and price at which forest biomass feedstocks are available. The total amount of forest derived woody biomass available at the landing for Clay County was found to be 44,338 dry Mg (49,265 odt) at prices ranging from \$11 to \$220 per dry Mg (\$10 to 200 per odt) (Table 5-2). Approximately, 72% of which is available at a price of \$66 per dry Mg (\$60 per odt). Figure 5-4A illustrates the supply curve for biomass feedstocks for Clay County, it can be easily seen that the slope of the supply curve quickly rises after reaching a price of approximately \$75 per Mg (\$67.50 per odt). It indicates an area of inelasticity in price; or even with large increases in price, the quantity of biomass that will be available to the market will not change much. Alternatively, while the total amount of biomass that is technically available is more than 44,000 dry Mg, the total that can reasonably expected to reach the market is less than 38,000 dry Mg or 86%, due to the rapidly increasing costs of accessing and harvesting the material.

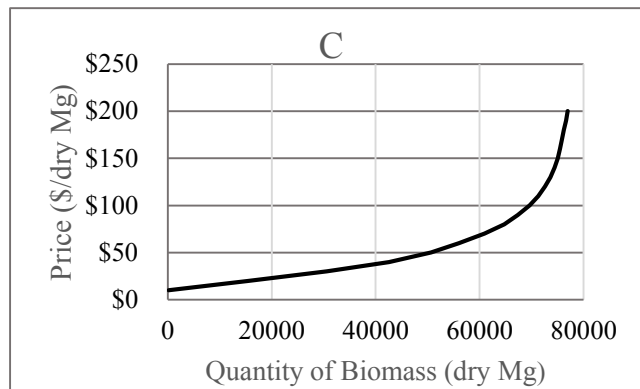
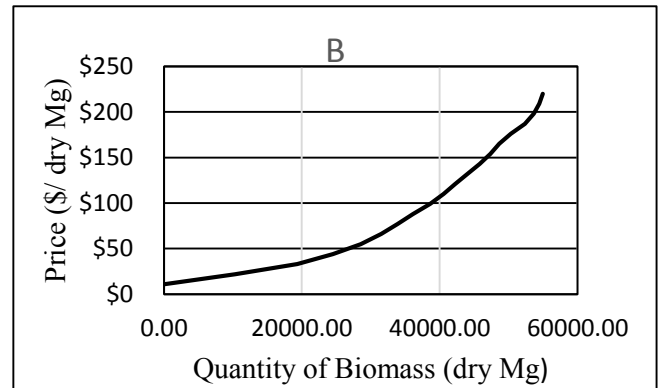
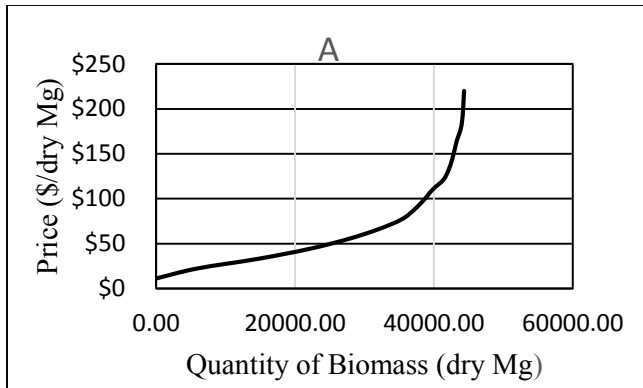


Figure 5-4 Supply Curve of Forest Derived Woody Biomass for (A) Clay County, (B) Fayette County and (C) Nicholas County, WV.

The total material availability for Fayette County was found to be 54970 dry Mg (61078 odt), with nearly 60% being available at a price of \$66 per dry Mg (\$60 per odt) (Table 5-2).

Figure 5-4B is the supply curve for Fayette County. The curve does not have such a pronounced inelastic region as the supply curve for Clay County. The absence of the inelastic region suggest that prices will increase proportionally with demand. Meaning in times where there is a shortage of supply, it would be possible to acquire more material if the facility is willing to pay more.

This differs from the situation in Clay County, where after a certain point it is not possible to pay enough to make up the missing demand.

Table 5-1 Biomass Quantities Available by Price for each County.

Price (\$/Mg)	Biomass Availability By County (Mg)			
	Clay	Fayette	Nicholas	Total
11	29	77	154	260
22	5867	10323	13891	30081
33	14794	19360	27519	61673
44	22097	24525	38314	84936
55	27689	28525	45611	101825
66	32069	31536	50385	113990
77	35389	33901	54843	124133
88	37209	36100	58300	131609
99	38608	38627	60609	137844
110	39802	40581	62649	143032
121	41366	42259	64140	147765
132	42109	44029	65286	151424
143	42589	45838	66254	154681
154	42958	47346	66983	157287
165	43303	48650	67515	159468
176	43801	50327	67905	162033
187	44053	52340	68238	164631
198	44180	53643	68596	166419
209	44251	54452	68969	167672
220	44338	54970	69236	168544

Finally, the total material availability for Nicholas County was found to be 69,236 dry Mg (76929 odt) of woody biomass. Similar to Clay County, slightly over 72% percent of the material is available at a price of \$66 per dry Mg (\$60 per odt). Also similar to Clay County the supply curve (Figure 5-4C) demonstrates that the price elasticity of supply becomes highly inelastic as it approaches the available capacity. Examination of the supply curve, indicates that after approximately \$66 per dry Mg, price increases will not return a quantity of supply that is

proportional to the price increase, and that the cost of recovering the nearly final 15,000 dry Mg of material would for all intents and purposes be too expensive, except in extreme cases.

The total available material available annually from the three counties totals 168,545 dry Mg (185,399 odt) at a price of \$220 per dry Mg (\$200 per odt), which is substantially more than the 109,000 dry Mg (120,000 odt) that are needed to supply a 10,000 bbl/day CBTL facility that is using 92% Coal and 8% biomass, however at \$220 per dry Mg the cost of feedstock would likely be too expensive to make financial sense. Through examination of the composite supply of the three counties it is determined that the requisite demand can be met at the price of \$66 per dry Mg, since it has been determined that approximately 113,991 dry Mg (126,657 odt) will be available at this price, using the assumptions of this study (Figure 5-7).

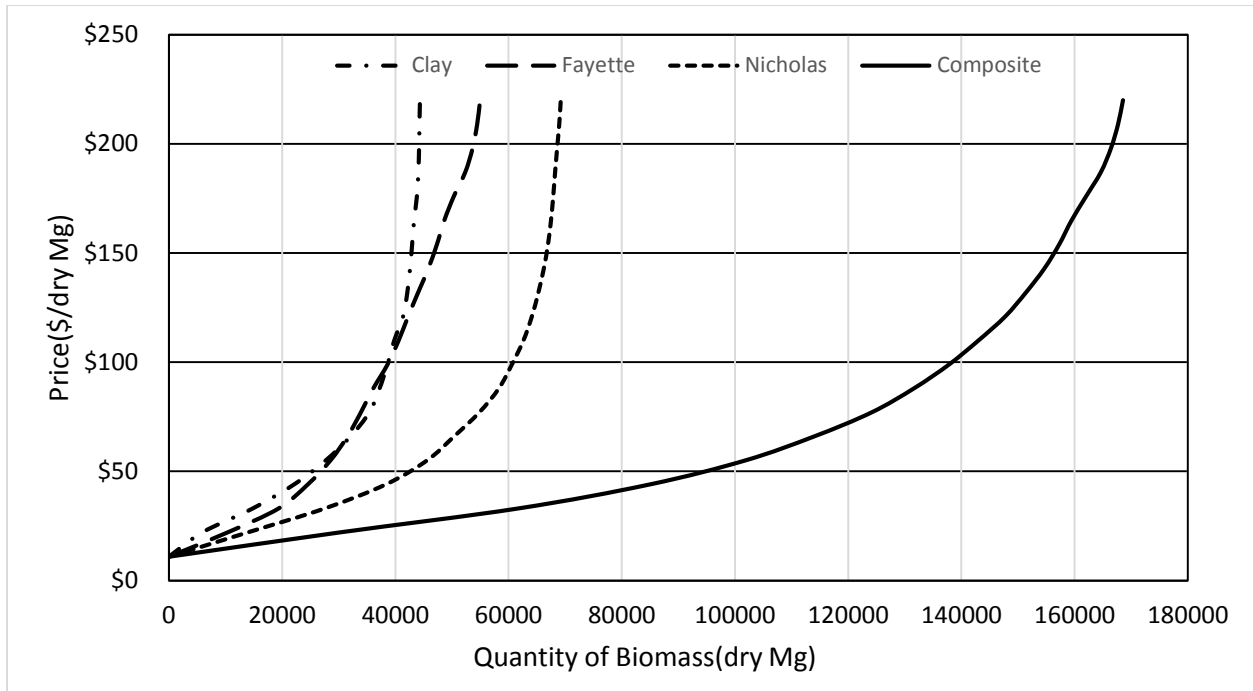


Figure 5-5 Composite Supply Curve of Woody Biomass for the Three County Procurement Area.

5.4.2 Comparison to Regional Estimates

The 2011 U.S. billion-ton update: biomass supply for a bioenergy and bioproducts industry (Perlack et al., 2011), is one of the most cited references that refers to estimates of woody biomass availability. The estimates of woody biomass were made for the United States at the county level, to estimate the ability to reach 1 billion dry tons of biomass feedstocks for the use in the energy and bioproducts industry. Table 5-3 provides the estimate of biomass availability from both the simulation and the billion-ton study along with the average percent difference for all prices between \$10 and \$200 per odt. Additionally, the results in the simulations have been reduced by 30% to account for the sustainability factor that is utilized by the Billion-ton study.

Table 5-2 Comparison of Simulation Results to the Billion-ton Study^a.

County	Simulation Results (odt)	Billion-ton Study (odt)	Mean difference (%)
Clay	34485	19200	60%
Fayette	42755	87300	-63%
Nicholas	53850	57100	-19%
Total	131090	163600	-34%

a. The results in this section have been converted to odt for comparison using the conversion factor of 1.1 odt per Mg.

It can be seen from Table 5-3 that there is a large difference between the results from the simulation and the billion ton study. In two of the three cases the billion-ton study estimated a higher level of material availability than our simulations. In the billion-ton study, it was necessary to make some broad assumptions based solely on large scale terrain factors and it was impractical to assess site accessibility at the forested parcel level for an analysis at the national level. Assessing harvesting cost at a county level resolution is likely to be one of the major factors contributing to the differences between the simulation results and the results of the billion-ton study. For example, the billion-ton study used a Forest Inventory and Analysis (FIA) variable that was the distance to the nearest road as a proxy for accessibility. This is likely the cause for the low estimate for Clay County, which has large roadless areas that are not counted toward the potential supply, when access is not truly limited. While this is adequate for a coarse resolution study, it is necessary to truly assess the path that must be taken to extract the material to be able to define the final cost. Similarly, it would not be practical to assess machine

movement on such a large scale as the terrain information that would be needed would most likely quickly become too large to be able to analyze in a reasonable manner.

5.5 CONCLUSIONS

Assessing the economic availability of biomass feedstocks is imperative for bioenergy projects that are in the final planning stages before construction. While there have been several studies that have been carried out on both the regional and national levels, neither type generally has the detail needed to truly inform the decisions of those that are investing in the development of these large projects. The ideal situation would be to complete a total inventory of all the available feedstocks that are within the potential procurement area, and this would not only be too costly and time consuming but also impractical. The modeling process and assessing method presented in this paper, provides a way to improve on the estimates that are given by the broader assessments, in a way that is cost effective and minimally time consuming. Additionally, this method is also flexible enough to be able to be modified to represent the harvesting operations that an individual may be using.

The results of the test case on a 10,000 bbl/day CBTL plant, returned an estimate of available feedstocks that were more conservative than those given by a large scale assessment. The methods employed were able to provide an estimate of both the availability and expected price, which can be used to aid in the further planning of the project. While it is not possible to completely validate the results at such a large scale, it is felt that the estimates were reasonable based on the assumptions that were utilized for the analysis. Additionally, the prices that were returned are in-line with the prices reported by the North American Wood Fiber Review (2013).

The simulation model was constructed using productivity and cost data for typical harvesting operations in the central hardwood region. The applicability of this model outside of this region, may require adjustments to account for differences in machinery and work method. Additionally, the costs related to harvesting tend to vary widely from region to region and should be examined if being used outside of the region for which it was created. Future development will include a more user friendly interface to allow access to more users, additionally the interface will also allow for the adjustment of factors that may vary between feedstock regions.

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6 SUMMARY

A combination of modeling techniques were used to examine the economics of the use of woody biomass for the development of a bio-energy industry in the Northeastern United States. Based on the results of the modeling processes and case scenarios, along with sensitivity analysis the following conclusions can be drawn:

- 1) The delivered cost of woody biomass feedstock for a base case scenario in which the facility requires 180,000 dry Mg(200,00 odt) per year ranged from \$70.91-\$76.19 per dry Mg, supporting 15 facilities of this size in the three state region of NY, PA and WV. With smaller demand levels it is possible to expand the number of facilities to 24 of the 25 potential candidate locations and the cost is also reduced to \$66.46-\$73.97 per dry Mg. Conversely when the demand exceeded 180,000 dry Mg per year (200,000 odt per year), cost dramatically increased to over \$80 per dry Mg and procurement areas grew rapidly; doubling the size of the procurement area in the base scenario, leading to fewer facilities that were able to be sited.
- 2) The findings suggest that, at least in the northeastern United States, that the locations of wood-based bio-energy facilities are not spatially dependent. Intuitively, since forested areas are not evenly distributed throughout the northeastern United States, it was assumed that would be intrinsic spatial correlation. However, the inclusion of timber products output in the final model is evidence that the facilities will be located in areas where forest and forest products are plentiful. Timber products output is basically a proxy for the amount of resource in an area; but additionally, areas that have a strong base in traditional forest products would also have an infrastructure in place for the transportation of the feedstocks. However, there is no evidence that

socio-economic factors such as unemployment, median household income, etc. are truly drivers of the development of bioenergy facilities, as had been suggested. The results did not point to any factors that would suggest that facilities are being located in areas of high unemployment to spur job growth or in low income levels as a community development and wealth creation tool. Additionally, since the price of energy was not found to be a significant factor, the evidence suggest that energy prices have not yet reached levels where the choice to change to an alternative energy source is being made. Again, this is a discrepancy with one of the cited reasons why bioenergy should be developed. Perhaps rising energy prices will be a driver for bioenergy in the future, but there is no evidence that that is currently the case.

3) Applying a two-stage site identification model in an 18 county area in southern West Virginia, and was successful in taking spatial data of differing scales and subject matter and integrating it together to identify and rank potential sites for CBTL facilities. It identified the Glade Creek area, near Summersville, WV as the most preferable location for development. In addition to selecting the site the inclusion of optimization modeling allows for the examination of factors that contribute to the rank and provides a basis for the investors for determining costs. The results can be utilized as inputs into financial models as the planning process continues.

4) Simulation of biomass extraction was used to examine if the study area identified for the establishment of a coal/biomass to liquids facility had access to sufficient levels of feedstocks in the areas that were identified as suppliers in the siting model. Through simulation it was determined that there would be nearly 114,000 dry Mg (126,667 odt) of material available at a price of \$66 per dry Mg (\$60 per odt) which is more than the requirement of the 10,000 bbl per day test case, which required 109,000 dry Mg (120,000 odt) per year.

APPENDIX A GAMS CODE FOR SUPPLY CHAIN OPTIMIZATION

```
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```

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```

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```

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$include "C:\Users\dhartle4\Documents\gamsdir\projdir\setm.inc"
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$include "C:\Users\dhartle4\Documents\gamssdir\projdir\setmhi.inc"
;/;
set mho(m)/
$include "C:\Users\dhartle4\Documents\gamssdir\projdir\setmho.inc"
;/;
set mpi(m)/
$include "C:\Users\dhartle4\Documents\gamssdir\projdir\setmpi.inc"
;/;
set mpo(m)/
$include "C:\Users\dhartle4\Documents\gamssdir\projdir\setmpo.inc"
;/;
set mhs(m)/Chip;/;
set mc/Chip,Pellet;/;
set mhp(m)/
$include "C:\Users\dhartle4\Documents\gamssdir\projdir\setmhp.inc"
;/;
set mhc(m)/Chip;/;
set msp(m)/Chip;/;
set msc(m)/
$include "C:\Users\dhartle4\Documents\gamssdir\projdir\setmsc.inc"
;/;
set mps(m)/
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set mpc(m)/
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```

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set psc(p)/
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;/
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;/
set j/
$include "C:\Users\dhartle4\Documents\gammdir\projdir\setj.inc"
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set c/
$include "C:\Users\dhartle4\Documents\gammdir\projdir\setc.inc"
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set t/
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```

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$include "C:\Users\dhartle4\Documents\gamsdir\projdir\parhc.inc"
/;
parameter scost(p)/
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\parscost.inc"
/;
parameter sloss(p)/
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\parsloss.inc"
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parameter scap(p)/
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/;
parameter pcost(p)/
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/;
parameter pfcost(p)/
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\procfc.inc"
/;
parameter pcap(p)/
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\parpcap.inc"
/;
table dem(m,c)
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\pardem.inc"
;
parameter mprice(m)/

```

```

$include "C:\Users\dhartle4\Documents\gamsdir\projdir\parmprice.inc"
/;
table bavail(i,m)
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\parbavail.inc"
;
table ijdist(i,j)
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\parijdist.inc"
;
table jkdist(j,j)
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\parjjdist.inc"
;
table itc(p,i)
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\paritc.inc"
;
table ta(t,m)
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\parta.inc"
;
parameter tc(m)/
$include "C:\Users\dhartle4\Documents\gamsdir\projdir\partc.inc"
/;

alias(j,k);

```

Variables

zh(p,i,t)	Harvest Level at location i during time t
zsc(p,j,t)	Chip Storage Level at location j during time t
zsp(p,j,t)	Pellet Storage Level at location j during time t

$zp(p,j,t)$	Processing Level at location j during time t
$xhs(m,i,j,t)$	Quantity of Material Shipped To Storage from Harvest Site
$xhp(m,i,j,t)$	Quantity of Material Shipped to Processing from Harvest Site
$xhc(m,i,j,t)$	Quantity of Material Shipped to Conversion from Harvest Site
$xsp(m,j,j,t)$	Quantity of Material Shipped to Processing from Storage
$xsc(m,j,j,t)$	Quantity of Material shipped to Conversion from Storage
$xps(m,j,j,t)$	Quantity of Material shipped to storage from processing
$xpc(m,j,j,t)$	Quantity of Material shipped to conversion from processing
$h(m,i,t)$	Amount of Material harvested from harvest site
$rc(m,j,t)$	Amount of Chip Material Remaining at storage site.
$rp(m,j,t)$	Amount of Pellet Material Remaining at storage site.
$sc(p,j,t)$	storage cost
pi	Total Profit
$\phi(t)$	Revenue for time period
$\phi_{ih}(t)$	Revenue from harvest materials
$\phi_{is}(t)$	Revenue from stored materials
$\phi_{ip}(t)$	Revenue from processed materials
$\eta(t)$	Harvesting Cost for time period
$\mu(t)$	Total Transportation Cost for time t
$\mu_h(t)$	Transport Cost for harvested material for a time period
$\mu_s(t)$	Transport Cost for stored material
$\mu_p(t)$	Transport cost between nodes for a time period
$\rho(t)$	Total Storage Cost for time period
$\rho_c(t)$	Storage Cost for chips
$\rho_p(t)$	Storage Cost for pellets
$\tau(t)$	Total processing Cost for time period
$\tau_c(t)$	Processing cost for chips
$\tau_p(t)$	Processing cost for pellets

$ys(p,j)$ Binary Variable for open storage facilities
 $yp(p,j)$ Binary Variable for open processing facilities
 $yc(m,c,j)$ Binary Variable for open conversion facilities
 $fdem(m,j,t)$
 $pdemu(p,j,t)$
 $pdeml(p,j,t)$
;

Positive Variables $zh, zp, zsc, zsp, xhc, xhp, xhs, xpc, xps, xsc, xsp, h, fdem, pdemu, pdeml$; Binary Variables yc, yp, ys ;

Equations

$HBI(m,i,t)$ Harvest Balance Inputs
 $HBO(m,i,t)$ Harvest Balance Outputs
 $PBI(m,j,t)$ Processing Balance Inputs
 $PBO(m,j,t)$ Processing Balance Outputs

 $SBC(m,j,t)$ Storage Balance Chips
 $SBP(m,j,t)$ Storage Balance Pellets
 $HAC(m,i,t)$ Harvest Availability Constraint
 $ProCapU(p,j,t)$ Processing Capacity Upper Bound
 $ProCapL(p,j,t)$ Processing Capacity Lower Bound
 $STCapC(p,j,t)$ Storage Capacity of Chips
 $STCapP(p,j,t)$ Storage Capacity of Pellets
 $CSP1$ Chip Storage during Period 1
 $PSP1$ Pellet Storage during Period 1
 $CSPS$ Quantity of Chips stored in Pellet Storage
 $PSCS$ Quantity of Pellets stored in Chip Storage
 $ISTOR(m,t)$ Initial Storage

FacDem(m,j,t)	Facility Demant
CDEMC(m,j,t)	Chip Demand for Conversion
CDEMP(m,j,t)	Chip Demand for Processing
POpen(j)	Processing Open
SCOpen(j)	Chip Storage Open
SPOpen(j)	Pellet Storage Open
HCost(t)	Harvest Cost
PRCost(t)	Processing Cost
STORC(t)	Storage Cost Chips
STORP(t)	Storage Cost Pellets
STOR(t)	Total Storage Cost
TCost(t)	Transportation Cost
HTCost(t)	Transport Cost Harvest
PTCost(t)	Transport Cost Processing
STCost(t)	Tranport Cost Storage
HRevenue(t)	Harvest Revenue
PRevenue(t)	Processing Revenue
SRevenue(t)	Storage Revenue
Revenue(t)	Revenue
Profit	Profit
;	

$$HBI(m,i,t).. \quad \text{sum}(p\$ph(p),a(m,p)*zh(p,i,t))\$mhi(m)+h(m,i,t)\$mhi(m)=g=0;$$

$$HBO(m,i,t).. \quad \text{sum}(p\$ph(p),a(m,p)*zh(p,i,t))\$mho(m)=g=\text{sum}(j,xhc(m,i,j,t))\$mhc(m)+\text{sum}(j,xhp(m,i,j,t))\$mhp(m)+\text{sum}(j,xhs(m,i,j,t))\$mhs(m);$$

PBI(m,j,t)..
 $\text{sum}(p\$pp(p),a(m,p)*z(p,j,t))\$mpi(m)+\text{sum}(i,xhp(m,i,j,t))\$mhp(m)+\text{sum}(k,xsp(m,k,j,t))\$mps(m)=g=0;$

PBO(m,j,t)..
 $\text{sum}(p\$pp(p),a(m,p)*z(p,j,t))\$mpo(m)=g=\text{sum}(k,xpc(m,j,k,t))\$mpc(m)+\text{sum}(k,xps(m,j,k,t))\$mps(m);$

SBC(m,j,t)..
 $\text{sum}(p\$psc(p),a("Chip",p)*zsc(p,j,t))+\text{sum}(i,xhs("Chip",i,j,t+1))+\text{sum}(k,xps("Chip",k,j,t+1))=e=\text{sum}(p\$psc(p),zsc(p,j,t+1))+\text{sum}(k,xsc("Chip",j,k,t+1))+\text{sum}(k,xsp("Chip",j,k,t+1));$

SBP(m,j,t)..
 $\text{sum}(p\$psp(p),a("Pellet",p)*zsp(p,j,t))+\text{sum}(k,xps("Pellet",k,j,t+1))=e=\text{sum}(p\$psp(p),zsp(p,j,t+1))+\text{sum}(k,xsc("Pellet",j,k,t+1));$

CSP1.. $\text{sum}((p,j),zsc(p,j,"t1"))=e=0;$

PSP1.. $\text{sum}((p,j),zsp(p,j,"t1"))=e=0;$

CSPS.. $\text{sum}((p,j,t)\$psp(p),zsc(p,j,t))=e=0;$

PSCS.. $\text{sum}((p,j,t)\$psc(p),zsp(p,j,t))=e=0;$

ISTOR(m,t).. $\text{sum}((j,k),xsc(m,j,k,"t1")+xsp(m,j,k,"t1"))=e=0;$

ProcDemU(p,j,t).. $\text{pdemu}(p,j,t)=e=\text{pcap}(p)*yp(p,j);$

ProcDemL(p,j,t).. $\text{pdeml}(p,j,t)=e=\text{pcap}(p)*yp(p,j)*.75;$

ProCapU(p,j,t).. $z(p,j,t)\$pp(p)=l=\text{pdemu}(p,j,t);$

ProCapL(p,j,t).. $zp(p,j,t)\$pp(p)=g=pdeml(p,j,t);$

STCapC(p,j,t).. $zsc(p,j,t)\$psc(p)=l=(scap(p)*ys(p,j))\$psc(p);$

STCapP(p,j,t).. $zsp(p,j,t)\$psp(p)=l=(scap(p)*ys(p,j))\$psp(p);$

FacDem(m,j,t).. $fdem(m,j,t)=e=sum(c,dem(m,c)*yc(m,c,j));$

CDEMC(m,j,t)..
 $sum(i,xhc("Chip",i,j,t))+sum(k,xpc("Chip",j,k,t))+sum(k,xsc("Chip",j,k,t))=e=fdem("Chip",j,t);$

CDEMP(m,j,t).. $sum(k,xpc("Pellet",j,k,t))+sum(k,xsc("Pellet",j,k,t))=e=fdem("Pellet",j,t);$

POpen(j).. $sum((m,c)\$mpc(m),yc(m,c,j))=l=1;$

SCOpen(j).. $sum(p\$psc(p),ys(p,j))=l=1;$

SPOpen(j).. $sum(p\$psp(p),ys(p,j))=l=1;$

HAC(m,i,t).. $h(m,i,t)=l=bavail(i,m)\$mhi(m)*ta(t,m)\$mhi(m);$

HCost(t).. $eta(t)=e=sum(p\$ph(p),sum(i,zh(p,i,t))*hc(p)+sum(i,zh(p,i,t)*itc(p,i)));$

PRCost(t)..
 $tau(t)=e=sum(p\$pp(p),(sum(j,zp(p,j,t))*pcost(p))+(sum(j,pfcost(p)*yp(p,j))));$

STORC(t)..
 $rhoc(t)=e=sum(p\$psc(p),sum(j,zsc(p,j,t)*sloss(p)*60)+sum(j,scost(p)*ys(p,j)));$

$$\text{STORP}(t).. \quad \text{rho}(t)=e=\text{sum}(p\$psp(p),\text{sum}(j,\text{zsp}(p,j,t)*0)+\text{sum}(j,\text{scost}(p)*\text{ys}(p,j)));$$

$$\text{STOR}(t).. \quad \text{rho}(t)=e=\text{rho}(t)+\text{rho}(t);$$

$$\text{HTCost}(t)..$$

$$\text{muh}(t)=e=\text{sum}(m,\text{sum}((i,j),\text{xhc}(m,i,j,t)*\text{ijdist}(i,j)*\text{tc}(m))+\text{sum}((i,j),\text{xhp}(m,i,j,t)*\text{ijdist}(i,j)*\text{tc}(m))+\text{sum}((i,j),\text{xhs}(m,i,j,t)*\text{ijdist}(i,j)*\text{tc}(m)));$$

$$\text{PTCost}(t)..$$

$$\text{mup}(t)=e=\text{sum}(m,\text{sum}((j,k),\text{xpc}(m,j,k,t)*\text{jkdist}(j,k)*\text{tc}(m))+\text{sum}((j,k),\text{xps}(m,j,k,t)*\text{jkdist}(j,k)*\text{tc}(m)));$$

$$\text{STCost}(t)..$$

$$\text{mus}(t)=e=\text{sum}(m,\text{sum}((j,k),\text{xsp}(m,j,k,t)*\text{jkdist}(j,k)*\text{tc}(m))+\text{sum}((j,k),\text{xsc}(m,j,k,t)*\text{jkdist}(j,k)*\text{tc}(m)));$$

$$\text{TCost}(t).. \quad \text{mu}(t)=e=\text{muh}(t)+\text{mup}(t)+\text{mus}(t);$$

$$\text{HRevenue}(t).. \quad \text{phih}(t)=e=\text{sum}(m\$mhc(m),\text{sum}((i,j),\text{xhc}(m,i,j,t))*\text{mprice}(m));$$

$$\text{PRevenue}(t).. \quad \text{phip}(t)=e=\text{sum}(m\$mpc(m),\text{sum}((j,k),\text{xpc}(m,j,k,t))*\text{mprice}(m));$$

$$\text{SRevenue}(t).. \quad \text{phis}(t)=e=\text{sum}(m\$msc(m),\text{sum}((j,k),\text{xsc}(m,j,k,t))*\text{mprice}(m));$$

$$\text{Revenue}(t).. \quad \text{phi}(t)=e=\text{phih}(t)+\text{phip}(t)+\text{phis}(t);$$

$$\text{Profit}.. \quad \text{pi}=e=\text{sum}(t,\text{phi}(t)-\text{eta}(t)-\text{tau}(t)-\text{mu}(t)-\text{rho}(t));$$

option threads=6;

model bio_fc /all/;

bio_fc.ResLim=259200;

bio_fc.OptCR=0.05;

*bio_fc.Cheat=100000

solve bio_fc using mip maximizing pi;

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx
Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx
Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx
Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx
Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx
Processing_Conversion!A1

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Processing_Storage!A1

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Processing_Trans!A1

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\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx ProcCapU!A1

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\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx PelletStorage!A1

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Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx
Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_Base1.xlsx Yearly_Profit!A1

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\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx
Harvest_Processing!A1

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\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx Processing_Trans!A1

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\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx ProcCapU!A1

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\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx ChipStorage!A1

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\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_5.xlsx Processing_Cost!A1

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\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx Harvest_Storage!A1

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Harvest_Processing!A1

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Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx
Processing_Storage!A1

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Processing_Trans!A1

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\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx PelletStorage!A1

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Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx
Conversion_Demand!A1

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\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_15.xlsx Harvest_Cost!A1

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*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_nf.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_nf.xlsx
Harvest_Conversion!A1

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Storage_Conversion!A1

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Storage_Processing!A1

*Conversion

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Conversion_Demand!A1

*Revenue and Cost

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*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_ns.xlsx HarvestMaterial!A1

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Harvest_Conversion!A1

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Harvest_Processing!A1

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*Processing

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Processing_Storage!A1

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Storage_Conversion!A1

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Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_ns.xlsx
Conversion_Demand!A1

*Revenue and Cost

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\$Ontext

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*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_xs.xlsx HarvestMaterial!A1

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Harvest_Conversion!A1

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Processing_Conversion!A1

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Processing_Storage!A1

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Processing_Trans!A1

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*Storage

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Storage_Conversion!A1

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Storage_Processing!A1

*Conversion

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Conversion_Demand!A1

*Revenue and Cost

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\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_xs.xlsx Harvest_Cost!A1

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*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx
Harvest_Processing!A1

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*Processing

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Processing_Conversion!A1

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Processing_Storage!A1

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Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_sm.xlsx Yearly_Profit!A1

\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_md.xlsx Yearly_Profit!A1

\$Offtext

*\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_lg.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_1g.xlsx Harvest_Cost!A1
\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_1g.xlsx Processing_Cost!A1
\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_1g.xlsx StorageCost!A1
\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_1g.xlsx Trans_Cost!A1
\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_1g.xlsx Yearly_Profit!A1
*\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhurtle4/Documents/OPT_RES_xl.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhurtle4/Documents/OPT_RES_xl.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhurtle4/Documents/OPT_RES_xl.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhurtle4/Documents/OPT_RES_xl.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhurtle4/Documents/OPT_RES_xl.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhurtle4/Documents/OPT_RES_xl.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhurtle4/Documents/OPT_RES_xl.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhurtle4/Documents/OPT_RES_xl.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhurtle4/Documents/OPT_RES_xl.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhurtle4/Documents/OPT_RES_xl.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_xl.xlsx Yearly_Profit!A1

\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_.xlsx Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_60.xlsx Yearly_Profit!A1

\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_70.xlsx Yearly_Profit!A1

\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_90.xlsx Yearly_Profit!A1

\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx
Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Revenue!A1
\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Harvest_Cost!A1
\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Processing_Cost!A1
\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx StorageCost!A1
\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Trans_Cost!A1
\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_100.xlsx Yearly_Profit!A1
\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx
Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_HC10L.xlsx Yearly_Profit!A1

\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Processing_Trans!A1

\$libinclude xldump pdem.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx
Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_HC5L.xlsx Yearly_Profit!A1

\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx
Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_HC5U.xlsx Yearly_Profit!A1

\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx ProcCapl!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx
Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_HC10U.xlsx Yearly_Profit!A1

\$Offtext

\$Ontext

\$libinclude xldump zh.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx Harvest!A1

\$libinclude xldump yp.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Processing_Open!A1

\$libinclude xldump yc.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Conversion_Open!A1

\$libinclude xldump ys.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx Storage_Open!A1

*Harvesting

\$libinclude xldump h.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx HarvestMaterial!A1

\$libinclude xldump xhc.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Harvest_Conversion!A1

\$libinclude xldump xhs.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Harvest_Storage!A1

\$libinclude xldump xhp.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Harvest_Processing!A1

\$libinclude xldump muh.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Harvest_Trans!A1

\$libinclude xldump zp.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx Processing!A1

*Processing

\$libinclude xldump xpc.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Processing_Conversion!A1

\$libinclude xldump xps.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Processing_Storage!A1

\$libinclude xldump mup.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Processing_Trans!A1

\$libinclude xldump pdeml.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx ProcCap!A1

\$libinclude xldump pdemu.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx ProcCapU!A1

*Storage

\$libinclude xldump zsc.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx ChipStorage!A1

\$libinclude xldump zsp.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx PelletStorage!A1

\$libinclude xldump xsc.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Storage_Conversion!A1

\$libinclude xldump xsp.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Storage_Processing!A1

*Conversion

\$libinclude xldump fdem.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Conversion_Demand!A1

*Revenue and Cost

\$libinclude xldump phi.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx Revenue!A1

\$libinclude xldump eta.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx Harvest_Cost!A1

\$libinclude xldump tau.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx
Processing_Cost!A1

\$libinclude xldump rho.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx StorageCost!A1

\$libinclude xldump mu.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx Trans_Cost!A1

\$libinclude xldump pi.l C:/Users/dhartle4/Documents/OPT_RES_ALL.xlsx Yearly_Profit!A1

\$Offtext

APPENDIX B R CODE FOR SAR-PROBIT AND PROBIT

```
\documentclass{article}

\begin{document}
\SweaveOpts{concordance=TRUE}
<<echo=False>>=
setwd("F:/Final_Paper")
library(xlsx)
library(spatialprobit)
dat<-read.xlsx("Biomass_Facility_Data.xlsx",sheetName="Biomass_Facility_Data")
attach(dat)
lat<-cbind(Lat[1:299])
long<-cbind(Long[1:299])
Y<-cbind(Biomass[1:299])
X1<-cbind(rep(1,299))
X2<-
cbind(Unemp[1:299],MHI2011[1:299],TPO_MCF[1:299],POP[1:299],RD_Dens[1:299],Elec[1:
299],Alt_Energy[1:299],Obama[1:299],CT[1:299],DE[1:299],ME[1:299],MD[1:299],MA[1:299
],NH[1:299],NJ[1:299],NY[1:299],PA[1:299],VT[1:299],RI[1:299])
X3<-cbind(TPO_MCF[1:299],Alt_Energy[1:299],NH[1:299])
X<-cbind(X1,X2)
colnames(X)=c("Intercept","Unemploy","MHI","TPO","POP","RD","EP","Energy","Obama","C
T","DE","ME","MD","MA","NH","NJ","NY","PA","VT","RI")
colnames(X2)=c("Unemploy","MHI","TPO","POP","RD","EP","Energy","Obama","CT","DE","
ME","MD","MA","NH","NJ","NY","PA","VT","RI")
colnames(X3)=c("TPO","Energy","NH")

W<-kNearestNeighbors(x=long,y=lat,k=8)
@
```

```
<<echo=True>>=
sarprobit.fit1<-sar_probit_mcmc(Y,X,W,ndraw=10200,burn.in=200)
summary(sarprobit.fit1)
impacts(sarprobit.fit1)
@
```

```
<<echo=true>>=
library(arm)
probit<-bayesglm(Y~X2,family=binomial (link="probit"),n.iter=10000)
summary(probit)
ProbitScalar<-mean(dnorm(predict(probit,type="link")))
MarginalEffects<-ProbitScalar*coef(probit)
summary(MarginalEffects)
pprobit<-predict(probit,type="response")
summary(pprobit)
table(true=Y, pred=round(fitted(probit)))
```

```
probit0<-update(probit,formula=Y~1)
McFadden<-1-as.vector(logLik(probit)/logLik(probit0))
McFadden
```

```
library(mcmc)
probit3<-bayesglm(Y~X3,family=binomial (link="probit"))
summary(probit3)
ProbitScalar<-mean(dnorm(predict(probit3,type="link")))
MarginalEffects<-ProbitScalar*coef(probit3)
MarginalEffects
pprobit2<-predict(probit3,type="response")
```

```
summary(pprobit)
table(true=Y, pred=round(fitted(probit)))

probit00<-update(probit3,formula=Y~1)
McFadden1<-1-as.vector(logLik(probit3)/logLik(probit00))
McFadden1
@

\end{document}
```

APPENDIX C GAMS CODE FOR OPTIMAL FACILITY LOCATION

```
set s;
set f;
set t;
parameter ba(s);
parameter avail(t);
parameter dist(s,f);

$call "del gdxcbtl.gdx"
$call gdxrw opt_data.xlsx o=gdxcbtl.gdx index=myindex!a1

$gdxin gdxcbtl
$load s f t ba avail dist
display s;
display f;
display t;
display ba;
display avail;
display dist;

variables

hc(s,t)    Quantity of Chips Harvested from Site s during Period t
hr(s,t)    Quantity of Residue Harvested from Site s during Period t
ctp(s,f,t) Quantity of Chips transported for processing from Site s to Facility f during Period t
rtp(s,f,t) Quantity of Residue transported for processing from Site s to Facility f during
Period t
```


$rts(s,f,t)$ Quantity of Residue transported for storage from Site s to Facility f during Period t
 $smp(f,t)$ Quantity of Stored Material Processed at Facility f during Period t
 $mpf(f,t)$ Quantity of Residue processed at Facility f during Period t
 $msf(f,t)$ Quantity of Residue stored at Facility f during Period t
 $y(f)$ Binary variable for open facility (1 if open--0 otherwise)

$Harv(t)$ Harvesting Cost
 $TransC(s,t)$ Transport Cost Chips
 $TransR(s,t)$ Transport Cost Residue
 $Trans(t)$ Transport Cost
 $Proc(t)$ Processing Cost
 $Z(t)$
 Tot
 ;

positive variables $hc, hr, ctp, rtp, rts, smp, mpf, msf$; binary variables y ;

equations

$HarvBal(s,t)$ Harvest Balance
 $ChipTBal(s,t)$ Chip Transport Balance
 $ResTBal(s,t)$ Residue
 $ProceBal(f,t)$ Processing Balance
 $StorBal(f,t)$ Storage Balance
 $StorCap(f,t)$ Storage Capacity
 $FeedReq(f,t)$ Feedstock Requirement
 $Open$ Constraint on open facilities
 $HCost(t)$ Harvesting Cost

TCostC(s,t)
 TCostR(s,t)
 TCost(t) Transportation Cost
 PCost(t) Processing Cost
 PerTot(t) Total Cost per Period
 OTot Overall Total
 startstor(f) Starting Storage
 stoproc(f,t)
 *facility Specified Facility
 ;

HarvBal(s,t).. $1.053*hc(s,t)+1.01*hr(s,t)=l=ba(s)*avail(t);$

ChipTBal(s,t).. $sum(f,ctp(s,f,t))=l=hc(s,t);$

ResTBal(s,t).. $sum(f,rtp(s,f,t)+rts(s,f,t))=l=hr(s,t);$

ProceBal(f,t).. $1.053*mpf(f,t)=l=sum(s,rtp(s,f,t))+smp(f,t);$

StorBal(f,t).. $msf(f,t-1)+sum(s,rts(s,f,t))=e=msf(f,t)+smp(f,t);$

StorCap(f,t).. $msf(f,t)=l=4800*y(f);$

FeedReq(f,t).. $sum(s,ctp(s,f,t))+mpf(f,t)=e=10000*y(f);$

Open.. $sum(f,y(f))=g=1;$

HCost(t).. Harv(t)=e=36.52*sum(s,hc(s,t))+27.4*sum(s,hr(s,t));

TCostC(s,t).. TransC(s,t)=e=sum(f,ctp(s,f,t)*dist(s,f)*0.17);

TCostR(s,t).. TransR(s,t)=e=sum(f,(rtp(s,f,t)+rts(s,f,t))*dist(s,f)*.27);

TCost(t)..

Trans(t)=e=sum((s,f),(ctp(s,f,t)*dist(s,f)*0.17)+((rtp(s,f,t)+rts(s,f,t))*dist(s,f)*.27));

Pcost(t).. Proc(t)=e=sum(f,mpf(f,t))*2.47;

PerTot(t).. Z(t)=e=Harv(t)+Trans(t)+Proc(t);

OTot.. Tot=e=sum(t,Z(t));

startstor(f).. msf(f,"1")=e=0;

*facility.. y("WashingtonHeights")=e=1;

stoproc(f,t).. smp(f,t)=l=msf(f,t-1);

option threads=7;

model CBTL_Opt /all/;

*bio_fc.ResLim=259200;

CBTL_Opt.OptCR=0.01;

*bio_fc.Cheat=100000

solve CBTL_Opt using mip minimizing Tot;

\$libinclude xldump hc.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx ChipHarv!A1
\$libinclude xldump hr.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx ResHarv!A1
\$libinclude xldump ctp.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx ChipTran!A1
\$libinclude xldump rtp.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx ResToProc!A1
\$libinclude xldump rts.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx ResToStor!A1
\$libinclude xldump smp.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx StorMatProc!A1
\$libinclude xldump mpf.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx MaterialProc!A1
\$libinclude xldump msf.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx MaterialStored!A1
\$libinclude xldump y.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx OpenFacility!A1
\$libinclude xldump Harv.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx HarvestingCost!A1
\$libinclude xldump TransC.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx TransCostChips!A1
\$libinclude xldump TransR.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx TransCostRes!A1
\$libinclude xldump Trans.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx TransCost!A1
\$libinclude xldump Proc.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx ProcessCost!A1
\$libinclude xldump Z.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx TotalCost(Period)!A1
\$libinclude xldump Tot.l C:/Users/dhartle4/Documents/CBTL_RES.xlsx Total!A1

APPENDIX D HARVESTING SIMULATION CODE

MAIN()

```
using System;
using System.Runtime;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.IO;
using System.Data;
using System.Threading;
using System.Threading.Tasks;
using Excel = Microsoft.Office.Interop.Excel;

namespace ConsoleApplication2
{
    class Program
    {
        static void Main(string[] args)
        {
            Console.WriteLine("Enter County for Analysis:");
            var county = Console.ReadLine();
            var countlow = county.ToLower();
            var count4 = countlow.Substring(0, 4);

            int directory =
Directory.GetFiles(@"C:\Users\dhartle4\Dropbox\WVU\WoodyBiomassHarvestSim\" +
count4).Length;

            for (int c =1; c <= directory; c++)
            {
                Console.WriteLine("\r Processing Forest Area:{0}
", c);

                //Initialize a new Graph
                Graph graph = new Graph();
                //Read Data from CSV file and Create graph
                string filePath =
@"C:\Users\dhartle4\Dropbox\WVU\WoodyBiomassHarvestSim\"+count4+"\"+ c + ".csv";
                CsvToGraph graphCreator = new CsvToGraph();
                var data = graphCreator.ReadCsv(filePath);
                graphCreator.ArraytoNode(data, graph);
                graphCreator.CreateConnections(graph);

                //Define Landing Locations
                LandingFinder landinglocator = new LandingFinder();
                var landings =
landinglocator.TrimLandingList(landinglocator.LandingLocator(graph), graph);
```

```

        Console.WriteLine("\r Number of Landings:{0}
", landings.Count);
        Thread.Sleep(3000);
        foreach (var l in landings)
        {
            var x = graph.Nodes.Where(s => s.Value.ID == 1);
            foreach (var y in x)
            {
                y.Value.isLanding = true;
            }
        }

        //Allocate Nodes to Landings
        DistanceCalculator distcalc = new DistanceCalculator();
        if (landings.Count < 1)
        {
            distcalc.DistCalc(graph, "1");
            foreach (var n in graph.Nodes.Where(x => x.Value.isLanding != true))
            {
                n.Value.AllocatedLanding = "1";
                n.Value.AllocatedDistance = n.Value.DistanceFromStart["1"];
            }
        }
        else
        {
            foreach (var l in landings)
            {
                distcalc.DistCalc(graph, l);
                foreach (var n in graph.Nodes.Where(x => x.Value.isLanding !=
true))
                {
                    var dist = n.Value.DistanceFromStart[l];
                    if (n.Value.AllocatedLanding == null && dist <
double.PositiveInfinity)
                    {
                        n.Value.AllocatedLanding = l;
                        n.Value.AllocatedDistance = dist;
                    }
                    else if (dist < double.PositiveInfinity && dist <
n.Value.AllocatedDistance)
                    {
                        n.Value.AllocatedLanding = l;
                        n.Value.AllocatedDistance = dist;
                    }
                }
            }
        }

        //
        PathCreator pathCreator = new PathCreator();
        var path = pathCreator.ReturnPath(landings, graph);

```

```

var excelApp = new Excel.Application();
var excelWB = excelApp.Workbooks.Add();
// string outpath = @"C:\Users\Damon\My Documents\WBET\Output\";
//string outfile2 = outpath + Path.GetFileNameWithoutExtension(filePath);

foreach (var l in landings)
{
    Excel.Worksheet ws=excelWB.Worksheets.Add();

    List<string> added = new List<string>();
    {
        var row=1;
        foreach (var n in graph.Nodes.Where(j => j.Value.AllocatedLanding
== 1))
        {
            foreach (var p in path[l + "-" + n.Key])
            {
                if (added.Contains(p))
                {
                    continue;
                }
                else
                {
                    var cost = graph.Nodes[p].CostPerTon;
                    if (cost > 0)
                    {
                        ws.Cells[row, 1] = 1;
                        ws.Cells[row, 2] = n.Key;
                        ws.Cells[row, 3] = cost;
                        row++;
                    }
                    else
                    {
                        continue;
                    }
                    added.Add(p);
                }
            }
        }
    }
    excelWB.SaveAs(@"C:\Users\dhartle4\Documents\WBET\Output\" + count4 + "_"
+ c + ".xlsx");
    excelWB.Close();
}
Console.WriteLine("Processing Complete [Press Enter to Close]");
Console.ReadLine();
}
}
}

```

GRAPH CLASS

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

namespace ConsoleApplication2
{
    public class Graph
    {
        internal IDictionary<string, Node> Nodes { get; private set; }

        public Graph()
        {
            Nodes = new Dictionary<string, Node>();
        }

        public void AddNode(string id, double x, double y, double z)
        {
            var node = new Node(id, x, y, z);
            Nodes.Add(id, node);
        }

        public void AddConnection(string fromNode, string toNode, double distance, double
travdist, bool twoWay)
        {
            Nodes[fromNode].AddConnection(Nodes[toNode], distance, travdist, twoWay);
        }
    }
}
```

NODE CLASS

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

namespace ConsoleApplication2
{
    internal class Node
    {
```



```

IList<NodeConnection> _connections;

internal string ID { get; private set; }

internal double X { get; set; }

internal double Y { get; set; }

internal double Z { get; set; }

internal bool isLanding { get; set; }

internal IDictionary<string,double> DistanceFromStart { get; set; }

internal double TravelDistFromStart { get; set; }

internal string AllocatedLanding { get; set; }

internal double AllocatedDistance { get; set; }

internal Node Pred { get; set; }

internal Node Post { get; set; }

internal double Payload { get; set; }

internal double Cost { get; set; }

internal int No_Trips { get; set; }

internal double CostPerTon { get; set; }

internal IEnumerable<NodeConnection> Connections
{
    get { return _connections; }
}

internal Node(string id, double x, double y, double z)
{
    ID = id;
    X = x;
    Y = y;
    Z = z;
    isLanding = false;
    DistanceFromStart = new Dictionary<string, double>();
    _connections = new List<NodeConnection>();
}

internal void AddConnection(Node targetNode, double distance, double travdist,
bool twoWay)
{
    if (targetNode == null) throw new ArgumentNullException("targetNode");
    if (targetNode == this) throw new ArgumentException("Node may not connect to
itself.");
    if (distance <= 0) throw new ArgumentException("Distance must be positive.");

```

```

        _connections.Add(new NodeConnection(targetNode, distance, travdist));
        if (twoWay) targetNode.AddConnection(this, distance, travdist, false);
    }
}

```

NODE CONNECTION CLASS

```

using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

namespace ConsoleApplication2
{
    internal class NodeConnection
    {
        internal Node Target { get; private set; }
        internal double Distance { get; private set; }
        internal double TravelDist { get; private set; }

        internal NodeConnection(Node target, double distance, double travdist)
        {
            Target = target;
            Distance = distance;
            TravelDist = travdist;
        }
    }
}

```

CSVTOGRAPH CLASS

```

using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.IO;

namespace ConsoleApplication2
{
    public class CsvToGraph
    {
        public string[][] ReadCsv(string filePath)
        {
            StreamReader sr = new StreamReader(filePath);
            var lines = new List<string[]>();

```

```

var Row = 0;
while (!sr.EndOfStream)
{
    string[] Line = sr.ReadLine().Split(',');
    lines.Add(Line);
    Row++;
    Console.WriteLine("\r{0}    ", Row);
}
var data = lines.ToArray();
return data;
}

public void ArraytoNode(string[][] array, Graph graph)
{
    var id = 0;
    foreach (string[] record in array)
    {
        id++;
        var x = Convert.ToDouble(record[0]);
        var y = Convert.ToDouble(record[1]);
        var z = Convert.ToDouble(record[2]);
        Console.WriteLine("\r {0} Nodes added to Graph    ", id);
        graph.AddNode(Convert.ToString(id), x, y, z);
    }
}

public void CreateConnections(Graph graph)
{
    foreach (var i in graph.Nodes)
    {
        var ikey = i.Key;
        var ivalue1 = i.Value.X;
        var ivalue2 = i.Value.Y;
        var ivalue3 = i.Value.Z;
        foreach (var j in graph.Nodes)
        {
            var jkey = j.Key;
            var jvalue1 = j.Value.X;
            var jvalue2 = j.Value.Y;
            var jvalue3 = j.Value.Z;
            if (jvalue1 == ivalue1 && jvalue2 == ivalue2 + 30 || jvalue1 ==
ivalue1 && jvalue2 == ivalue2 - 30 || jvalue1 == ivalue1 + 30 && jvalue2 == ivalue2 ||
jvalue1 == ivalue1 - 30 && jvalue2 == ivalue2 || jvalue1 == ivalue1 + 30 && jvalue2 ==
ivalue2 + 30 || jvalue1 == ivalue1 + 30 && jvalue2 == ivalue2 - 30 || jvalue1 == ivalue1
- 30 && jvalue2 == ivalue2 + 30 || jvalue1 == ivalue1 - 30 && jvalue2 == ivalue2 - 30 ||
jvalue1 == ivalue1 + 30 && jvalue2 == ivalue2 + 60 || jvalue1 == ivalue1 + 30 && jvalue2
== ivalue2 - 60 || jvalue1 == ivalue1 - 30 && jvalue2 == ivalue2 + 60 || jvalue1 ==
ivalue1 - 30 && jvalue2 == ivalue2 - 60 || jvalue1 == ivalue1 + 30 && jvalue2 == ivalue2
+ 90 || jvalue1 == ivalue1 + 30 && jvalue2 == ivalue2 - 90 || jvalue1 == ivalue1 - 30 &&
jvalue2 == ivalue2 + 90 || jvalue1 == ivalue1 - 30 && jvalue2 == ivalue2 - 90 || jvalue1
== ivalue1 + 60 && jvalue2 == ivalue2 + 30 || jvalue1 == ivalue1 + 60 && jvalue2 ==
ivalue2 - 30 || jvalue1 == ivalue1 - 60 && jvalue2 == ivalue2 + 30 || jvalue1 == ivalue1
- 60 && jvalue2 == ivalue2 - 30 || jvalue1 == ivalue1 + 60 && jvalue2 == ivalue2 - 90 ||
jvalue1 == ivalue1 + 60 && jvalue2 == ivalue2 - 90 || jvalue1 == ivalue1 - 60 && jvalue2
== ivalue2 + 90 || jvalue1 == ivalue1 - 60 && jvalue2 == ivalue2 - 90 || jvalue1 ==

```



```

        InitialiseGraph(graph, startingNode);
        ProcessGraph(graph, startingNode);
    }

    public Dictionary<string, double> CalculateDistances(Graph graph, string
startingNode)
    {
        if (!graph.Nodes.Any(n => n.Key == startingNode))
            throw new ArgumentException("Starting node must be in graph.");

        InitialiseGraph(graph, startingNode);
        ProcessGraph(graph, startingNode);
        return ExtractDistances(graph, startingNode);
    }

    public IList<string> ReturnPath(Graph graph, string startingNode, string
endingNode)
    {
        if (!graph.Nodes.Any(n => n.Key == startingNode))
            throw new ArgumentException("Starting node must be in graph.");
        if (!graph.Nodes.Any(n => n.Key == endingNode))
            throw new ArgumentException("Ending node must be in graph.");
        return ExtractPath(graph, startingNode, endingNode);
    }

    private void InitialiseGraph(Graph graph, string startingNode)
    {
        foreach (Node node in graph.Nodes.Values)
            node.DistanceFromStart[startingNode] = double.PositiveInfinity;
        graph.Nodes[startingNode].DistanceFromStart[startingNode] = 0;
    }

    private void ProcessGraph(Graph graph, string startingNode)
    {
        bool finished = false;
        var queue = graph.Nodes.Values.ToList();
        while (!finished)
        {
            Node nextNode = queue.OrderBy(n =>
n.DistanceFromStart[startingNode]).FirstOrDefault(n =>
!double.IsPositiveInfinity(n.DistanceFromStart[startingNode]));
            if (nextNode != null)
            {
                ProcessNode(nextNode, startingNode, queue);
                queue.Remove(nextNode);
            }
            else
            {
                finished = true;
            }
        }
    }

    private void ProcessNode(Node node, string startingNode, List<Node> queue)
    {

```

```

        var connections = node.Connections.Where(c => queue.Contains(c.Target));
        foreach (var connection in connections)
        {
            double distance = node.DistanceFromStart[startingNode] +
connection.Distance;
            double travdist = node.TravelDistFromStart + connection.TravelDist;
            if (distance < connection.Target.DistanceFromStart[startingNode])
            {
                connection.Target.DistanceFromStart[startingNode] = distance;
                connection.Target.TravelDistFromStart = travdist;
                connection.Target.Pred = node;
                node.Post = connection.Target;
                Console.WriteLine("\r Processing Node:{0}", node.ID);
            }
        }
    }

    private Dictionary<string, double> ExtractDistances(Graph graph, string
startingNode)
    {
        return graph.Nodes.ToDictionary(n => n.Key, n =>
n.Value.DistanceFromStart[startingNode]);
    }

    private IList<string> ExtractPath(Graph graph, string start, string end)
    {
        IList<string> Path=new List<string>();
        if (end != start)
        {
            while (end != start)
            {
                Path.Add(end);
                if (graph.Nodes[end].AllocatedDistance == 0)
                {
                    break;
                }
                else
                {
                    end = graph.Nodes[end].Pred.ID;
                }
            }
            Path.Add(start);
        }
        return Path;
    }
}
}
}

```

LANDING FINDER CLASS

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Threading;

namespace ConsoleApplication2
{
    public class LandingFinder
    {
        public List<string> LandingLocator(Graph graph)
        {
            double s1 = 0;
            double s2 = 0; double s3 = 0; double s4 = 0; double s5 = 0; double s6 = 0;
            double s7 = 0; double s8 = 0;
            var counter = 0;
            List<string> list = new List<string>();
            foreach (var l in graph.Nodes)
            {
                counter++;
                var lvalx = l.Value.X;
                var lvaly = l.Value.Y;
                var lvalz = l.Value.Z;
                foreach (var s in graph.Nodes)
                {
                    var svalx = s.Value.X;
                    var svaly = s.Value.Y;
                    var svalz = s.Value.Z;
                    if (svalx == lvalx - 30 && svaly == lvaly + 30)
                    {
                        s1 = (svalz - lvalz) / Math.Sqrt(Math.Pow(svalx - lvalx, 2) +
Math.Pow(svaly - lvaly, 2));
                    }

                    if (svalx == lvalx && svaly == lvaly + 30)
                    {
                        s2 = (svalz - lvalz) / Math.Sqrt(Math.Pow(svalx - lvalx, 2) +
Math.Pow(svaly - lvaly, 2));
                    }

                    if (svalx == lvalx + 30 && svaly == lvaly + 30)
                    {
                        s3 = (svalz - lvalz) / Math.Sqrt(Math.Pow(svalx - lvalx, 2) +
Math.Pow(svaly - lvaly, 2));
                    }

                    if (svalx == lvalx - 30 && svaly == lvaly)
                    {
                        s4 = (svalz - lvalz) / Math.Sqrt(Math.Pow(svalx - lvalx, 2) +
Math.Pow(svaly - lvaly, 2));
                    }
                }
            }
        }
    }
}
```

```

        if (svalx == lvalx + 30 && svaly == lvaly)
        {
            s5 = (svalz - lvalz) / Math.Sqrt(Math.Pow(svalx - lvalx, 2) +
Math.Pow(svaly - lvaly, 2));
        }

        if (svalx == lvalx - 30 && svaly == lvaly - 30)
        {
            s6 = (svalz - lvalz) / Math.Sqrt(Math.Pow(svalx - lvalx, 2) +
Math.Pow(svaly - lvaly, 2));
        }

        if (svalx == lvalx && svaly == lvaly - 30)
        {
            s7 = (svalz - lvalz) / Math.Sqrt(Math.Pow(svalx - lvalx, 2) +
Math.Pow(svaly - lvaly, 2));
        }

        if (svalx == lvalx + 30 && svaly == lvaly - 30)
        {
            s8 = (svalz - lvalz) / Math.Sqrt(Math.Pow(svalx - lvalx, 2) +
Math.Pow(svaly - lvaly, 2));
        }
    }

    Console.WriteLine("\r Node Checked:{0}
", counter);
    if (Math.Abs(s1) <= .05 && Math.Abs(s2) <= .05 && Math.Abs(s3) <= .05 &&
Math.Abs(s4) <= .05 && Math.Abs(s5) <= .05 && Math.Abs(s6) <= .05 && Math.Abs(s7) <= .05
&& Math.Abs(s8) <= .05)
    {
        list.Add(l.Value.ID);
        Console.WriteLine("\r Landing Added:{0}
", l.Value.ID);
    }
}

Console.WriteLine("\r Number of Landing Candidates:{0}", list.Count);
Thread.Sleep(3000);
return list;
}

public List<string> TrimLandingList(List<string> list, Graph graph)
{
    var candidate = list;
    List<string> final=new List<string>();
    for (int i = 0; i < list.Count; i++)
    {
        var current = list[i];
        var currentx = graph.Nodes[current].X;
        var currenty = graph.Nodes[current].Y;
        bool contain_can=candidate.Contains(current);
        bool contain_fin=final.Contains(current);
        if (contain_can==true && contain_fin==false)
        {

```



```

        final.Add(current);
        var remove = graph.Nodes.Where(y => Math.Abs(y.Value.X - currentx) > 1
&& Math.Abs(y.Value.X - currentx) < 630 || Math.Abs(y.Value.Y - currenty) > 1 &&
Math.Abs(y.Value.Y - currenty) > 630 && y.Value.ID != current);
        foreach (var r in remove)
        {
            candidate.Remove(r.Key);
            Console.WriteLine("\r Point {0} removed
", r.Key);
        }
    }
}
return final;
}
}
}

```

PATHCREATOR CLASS

```

using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

namespace ConsoleApplication2
{
    public class PathCreator
    {
        public Dictionary<string, List<string>> ReturnPath(List<string>list, Graph graph)
        {
            Dictionary<string, List<string>> path = new Dictionary<string,
List<string>>();
            var calculator = new DistanceCalculator();
            if (list.Count >= 1)
            {
                foreach (string land in list)
                {
                    var allocLand = graph.Nodes.Where(l => l.Value.AllocatedLanding ==
land && l.Value.AllocatedLanding != null);
                    foreach (KeyValuePair<string, Node> n in allocLand)
                    {
                        List<string> pathNodes = new List<string>();
                        var end = n.Key;
                        string pathkey = land + "-" + end;
                        var paths = calculator.ReturnPath(graph, land, end);
                        var c=1;
                        var point=1;
                        foreach (string p in paths)
                        {
                            pathNodes.Add(p);
                        }
                    }
                }
            }
        }
    }
}

```

```

        point++;
    }
    c++;
    pathNodes.Reverse();
    path.Add(pathkey, pathNodes);

    double limit_pay = 22000;
    var pathorder = path[land + "-" + n.Key].ToList();
    pathorder.Reverse();
    foreach (var o in pathorder)
    {
        if (graph.Nodes[o].Post != null)
        {
            var firstx = graph.Nodes[o].X;
            var firsty = graph.Nodes[o].Y;
            var firstz = graph.Nodes[o].Z;
            var nextx = graph.Nodes[o].Post.X;
            var nexty = graph.Nodes[o].Post.Y;
            var nextz = graph.Nodes[o].Post.Z;
            var slope = -(nextz - firstz) / Math.Sqrt(Math.Pow(nextx
- firstx, 2) + Math.Pow(nexty - firsty, 2));
            var wt = 23690;
            var speed = 5;
            var force = 0.8971 * Math.Exp(-0.262 * speed) * 44000;
            var theta = Math.Atan(slope);
            var payload = ((2 * force) - (0.4 * wt * Math.Cos(theta))
- (2 * wt * Math.Sin(theta))) / ((1.05 * Math.Cos(theta)) + (2 * Math.Sin(theta)));
            Random random = new Random();
            var nontravel = random.Next(180, 300);
            var cycletime = graph.Nodes[o].Post.AllocatedDistance /
(speed * .44704) + 289.8;

            double costperturn = 0;
            if (payload < limit_pay)
            {
                limit_pay = payload;
                graph.Nodes[o].Post.Payload = limit_pay;
                costperturn = ((cycletime / 3600) * 81.34);
                graph.Nodes[o].Post.Cost = costperturn;
                if (limit_pay > 3822)
                {
                    graph.Nodes[o].Post.No_Trips = 1;
                }
                else
                {
                    graph.Nodes[o].Post.No_Trips =
(int)Math.Ceiling(3822 / limit_pay);
                }
                graph.Nodes[o].Post.CostPerTon = (.35*costperturn *
graph.Nodes[o].Post.No_Trips / 1.275)+13.70;
            }
            else
            {
                graph.Nodes[o].Post.Payload = limit_pay;
                costperturn = ((cycletime / 3600) * 81.34);
                graph.Nodes[o].Post.Cost = costperturn;
            }
        }
    }
}

```