LOGISTIC MODELING OF A BIOMASS UTILIZATION SYSTEM

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by

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

LOGISTIC MODELING OF A BIOMASS UTILIZATION SYSTEM

presented by Maetee Patana-Anake

a candidate for the degree of Master of Science

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ABSTRACT

A logistic model was developed for a biomass utilization system and implemented in ExtendSim. The model allows for system simulation and analysis of biomass supply chain in terms of economic viability and energy balance. The supply chain network was divided into three main subsystems including crop production, biomass handling and logistics, and biomass processing. After validation, the model was used to simulate different conditions and practices so that favorable system configurations and realistic limitations could be determined to maximize net energy output and economic viability. The model was based on the operation of Show Me Energy Coop, a local biomass pelletization plant near Centerview, MO. The simulation results indicated potential benefits from increased truck capacity for transportation, expanded plant capacity, and improved process throughput. The study also suggested that corn stover, a biomass material the plant uses, provides better performance than other biomass materials such as switchgrass and miscanthus.

CHAPTER 1

INTRODUCTION

1.1 Problem statement

To meet the high energy demand, there is a need for new energy sources to substitute fossil-based energy, which is unsustainable and soon to be depleted. Renewable energy is energy generated from natural resources and believed to be the most promising substitution for fossil-based energy source, owing the re-production ability and potential for reducing carbon dioxide in the environment. Biomass is a type of renewable energy from living or recently died biological materials such as crop or residues. Biomass crops can be grown on several types of terrain. This provides flexibility to biomass production in different areas. With this incentive, the Biomass Research and Development Technical Advisory Committee foresees the need for biomass and sets the goal to replace 30% of the petroleum consumption to biobased products, such as ethanol and biodiesel by 2030 (DOE, 2003). Approximately 1 billion dry tons of lignocellulosic feedstock from biomass is needed annually to achieve the goal.

Biomass is widely used as a heating source and is a material for biofuels production. At the current state of technology, biomass has a relatively low price compared to other types of renewable energy. The price ranges from 3 to 12 cents per kWh (Johansson & Goldemberg, 2004). Biomass can also be easily stored and transported by using common transportation systems which may result in lower storage and handling costs.

Biomass material is generally collected from close-by biomass material production locations in a circular shape with the processing plant located in the middle to minimize transport distance between the plant and the material collection sites (Gallagher et al., 2003). For a sufficient biomass supply, required cultivation land size can be estimated from the total demand of biomass material and the biomass yield. Each type of biomass requires a different amount of cultivation input, hence are differences in cost and energy inputs per dry ton. Variations of inputs are also present in biomass transportation and biomass processing where different machines and handling methods can be customized to match with the material form and conditions. These variations result in differences in total costs and total energy input.

To compete with and replace fossil-based energy, cost minimization can be done through biomass selection and operation optimization. However, because of the variations in input and operations in the system, it is difficult to find the most suitable way to organize the biomass utilization system, especially with mixed biomass materials, which is believed to help lower capital costs of the system.

Economic viability and net energy output are two aspects that need to be addressed. A net benefit of each party in the supply chain is necessary to ensure economic viability. A positive net difference between the total energy output and the total energy input is necessary for maintaining energetic sustainability.

1.2 Research objectives

The overall goal of this study was to develop a logistic model for a biomass utilization system for analysis of economic viability and energetic sustainability of the system. The specific objectives were to:

1. Develop a logistic simulation model based on the operations of an actual biomass utilization system, and
2. Simulate the economic and the energetic states under various conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Biomass production and utilization system

A biomass production and utilization system is composed of three sub-systems including *biomass material production*, *biomass handling and preprocessing* (Sokhansanj et al., 2003). The three sub-systems are shown in **Figure 2.1**.

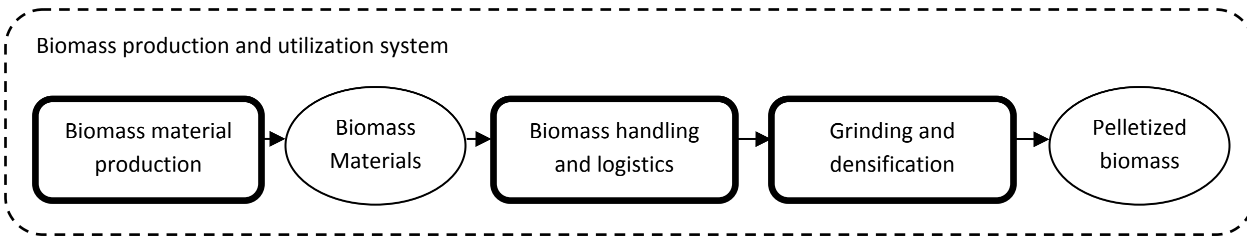

Figure 2.1 Overall structures of biomass production and utilization

2.2 Biomass material production

In order to replace fossil-based energy sources with biomass, the cost of energy production from biomass needs to be at least equal to or lower than the cost of the current energy production from fossil-based energy sources. To achieve this goal, production of different biomass materials are studied to identify potential biomass resources. In this study, biomass from crops and biomass from crop residues are considered.

Biomass material selection has been studied by a number of researchers. Huang et al. (2009) studied four different biomass crops: corn stover, switchgrass, hybrid poplar, and aspen wood. The total cost for cultivation, collection, and transportation was estimated based on data from published literature. The cost of corn stover cultivation, excluding the cost of nutrient replacement, is identified at $11 per ton. This is in contrast to the fact that corn stover is residue from grain production and, therefore, cultivation cost should not be applied as input cost as mentioned by Gallangher et al. (2003). Ethanol yield from lignocelluloses is also estimated and compared based on chemical composition and elementary composition of each biomass species. From comparison, it shows that ethanol production performance is a linear function of holocellulose composition in the biomass material. Hence, aspen wood, which is high in holocellulose, has the highest production yield per dry ton of biomass. This study also shows that the cost per unit of ethanol from corn stover is the lowest because of the low cost of material production combined with its high yield (dry ton ha^{-1}).

Corn stover has high potential as a biomass feedstock because of the abundant cultivation in the U.S. (DOE, 2003). Corn stover has an estimated yield of 5.7 dry ton ha^{-1} (Sokhansanj et al., 2006) and is also considered as a residue from grain production which has a low input cost. It is assumed that there is no input cost or input energy for biomass residue, with the exception of the cost of nutrient replacement at $4.64 dry ton^{-1} for extra fertilizing in land preservation (Petrolia, 2008).

Researchers also pay high attention to switchgrass because of its relative high yield of biomass and low cultivation inputs. Switchgrass, a U.S. native plant, is a tall-growing, warm-season, perennial grass. It can be grown easily in the mid-US. It has been used mostly for forage, wildlife, and land conservation purposes. The cultivation of switchgrass begins in early spring (USDA, 2001). The yields of biomass have been studied in 11 states across the U.S. with reported yields ranging from 8.5 to 20 dry ton ha^{-1} (Mclaughlin & Kszos, 2005). Huang et al. (2009) and Kumar and Sokhansanj (2007) reported that switchgrass average yield is estimated at 11 dry tons ha^{-1}, while the average yield is reported at 8.5 dry tons ha^{-1} in southern Iowa (Duffy, 2008). In small experiment fields, switchgrass yields have ranged from 2.55 to 17 dry tons ha^{-1} (Di Vergilio et al., 2007).

Fertilization can enhance the yield of switchgrass. To improve utilization of fertilizer on the field, the effect of varying amounts of nitrogen fertilizer on switchgrass yield was studied over a five-year period by Lemus et al. (2008). The experiment was conducted in Southern Iowa from 1998 to 2002. Two farms in different locations were selected. Five replications were randomly assigned to each farm, and four small fields were randomly assigned to each replication with varying amounts of fertilizer application: 0, 56, 112, and 224 kg N ha^{-1}. Nitrogen fertilizer use efficiency (FUE) and biomass quality analysis were calculated based on output yield, which were measured yearly. The biomass yield of switchgrass shows an increasing trend from 1998 to 2002, representing a positive cumulative effect of nitrogen (N) fertilization over time. The response of yield to N fertilizer was non–linear and declining as N levels increased. The trend of response of yield to N fertilizer is shown in **Figure 2.2.**

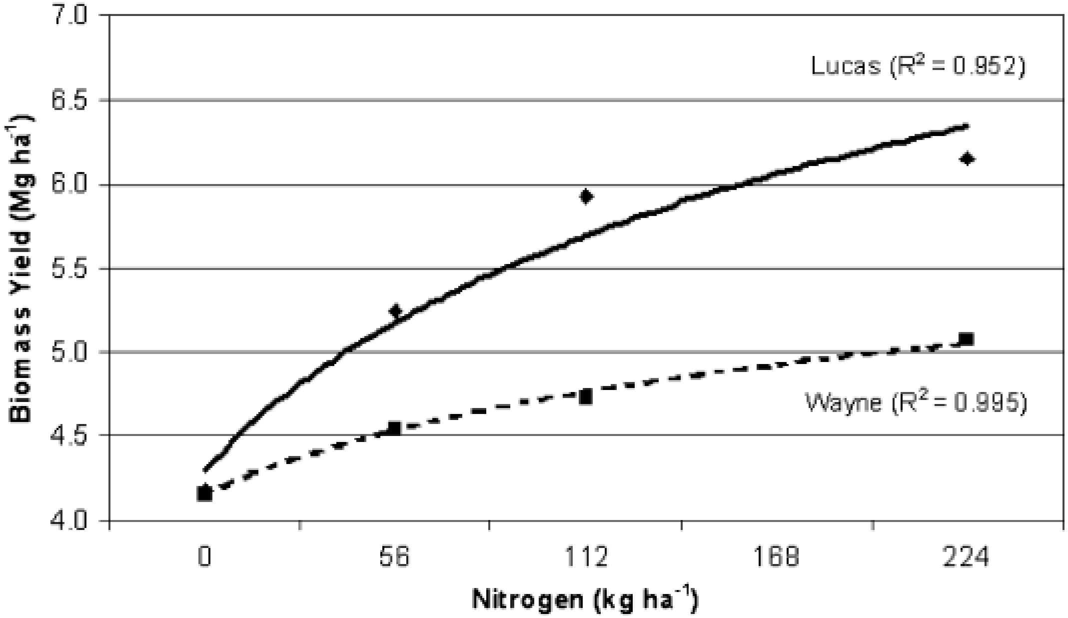

Figure 2.2 Switchgrass biomass yield at two locations fertilized with 0, 56, 112, or 224 kg N ha^{-1} (Lemus et al.,2008)

The result comparison shows that neither the nitrogen rate nor the location affected the energy concentration or quality of switchgrass material. It is suggested that harvesting of switchgrass should take place between September and November when optimum nitrogen fertilizer rates are between 56 to 112 kg N ha^{-1}.

Costs involved in biomass crop cultivation vary based on practice and cultivation location. Average financial and energy inputs per hectare of switchgrass production are presented in several research papers. Pimentel and Patzek (2005) estimated the average input for ethanol production from corn, switchgrass and wood. Inputs in terms of cost and energy are identified; however, there are no descriptions of the input source in detail. It is suggested that converting switchgrass into ethanol may return a negative net energy output. However, because of variation in practice and management, it is expected that optimization of operation and better conversion technology will provide more promising results. Duffy (2008) also investigated production costs and harvesting costs of switchgrass in detail. Although energy usage is not included, the research work provides detailed information of the operation and the amount of input required for switchgrass cultivation starting from land preparation, seeding, irrigation, and fertilizer and herbicide applications. In contrast to other research, it assumes that cultivation fields need to be reseeded 25% at a time, instead of starting all over every year. The estimated delivery price of biomass to the processing plant is $113 per ton. It should be mentioned that the yield of switchgrass from the area is relatively low at 10 ton ha^{-1} and fertilizer input is a lot higher than the optimal rate identified by Lemus et al. (2008).

A multi-biomass approach is expected to reduce biomass production cost by sharing capital equipment for multi-biomass. A few studies suggest that a combination of two biomass materials leads to a total cost reduction of about 15%-20% compared to single-biomass material. Rentizelas et al. (2009) also analyzed the multi-biomass approach and indicated that multi-biomass provides significant savings on storage, especially in relatively expensive storage systems. Lower maximum storage and smoother material flow result from different maturity times of materials.

Crop rotation is also another issue in multi-biomass utilization (Power et al., 2008). Cost and effect on ethanol production using a combination of three potential crops: wheat, barley, and sugar beet were studied. Three scenarios of crop rotation are (1) wheat, barley, and sugar beet, (2) wheat and sugar beet, (3) wheat only. Sugar beet should only be planted in an area of land once every three years. Other crops can be planted in off-years, but sugar beet should not be planted on the same site without crop rotation. Therefore, sugar beet needs to be cultivated with other biomass crops. The research results are shown in **Table 2.1.**

Table 2.1 – Multi-biomass utilization simulation results (Power et al., 2008)

Scenarios	No. of facilities	Ethanol Production	Capital Cost (€)	Production Cost (€)
Wheat, barley , and sugar beet	2	158,278,331	135,560,230	0.7
Wheat, and Sugar beet	2	175,534,632	145,847,534	0.69
Wheat	1	150,930,557	110,556,438	0.6

From the study, wheat only (scenario 3) provides the lowest production cost of €0.6 per liter; however, sugar beet provides the highest outcome in terms of ethanol and energy return per land unit.

It must also be mentioned that this crop rotation research was conducted in Europe. The results may not be applied to biomass utilization systems in U.S., because of differences in production costs, transportation systems, biomass crop types, and policies. However, it still provides a good reference, showing the limitations and advantages of multi-biomass systems compared to the single-biomass approach.

Input energy in biomass production either comes directly from fossil-fuel or other agricultural inputs which may also consume energy to produce. In the study by West and Marland (2002), input energy in the cultivation processes of corn, soy bean, and winter wheat are investigated. Energy content of fossil-fuel and electricity are considered to be direct energy usage, while indirect input energy from agricultural inputs (pesticide, fertilizer, irrigation water, and seed) are also included in the system. Energy involved in cultivation of corn, soybean, and winter wheat is calculated based on estimated amounts of inputs per unit land and energy per unit input. This research provides insight into energy usage in the cultivation process; but information relating to energy output from the biomass was not provided.

2.3 Biomass handling and pre-processing

2.3.1 Biomass handling operations

Different types of biomass require different handling methods within a biomass supply system. A review of operations involved in biomass supply systems was done by Sokhansanj et al., (2003) aiming to create an overall framework of the biomass supply system and to identify alternate ways to handle different types of biomass material with the appropriate tools and machines. The sequence of operations in the field, the countryside, and the refinery are broken down into details. Details of operations and tools are shown in **Table 2.2.**

Table 2.2. Entire biomass to feedstock handling system (Sokhansanj et al., 2003)

Location or activity center	Major operation	Process	Equipment
FIELD	cut & gather	Mowing conditioning	SP Mower – conditioner, disc, sickle, flail
		Raking, tedding, inverting	Rake, tedder, inverter
		Flail shredding and gathering	Flail cutter and windrower
		Combine straw management system	Combine mounted residue chopper and distributor
	Package	Round baling	Round baler with or without crop processor
		Square baling	Large square baler
		Forage harvesting - loose	SP chopper and wagon
		Field cubing	SP or pull type field cuber
	Haul & Store in the field	Round bales to field edge - tarping	Automatic bale pickup and mover
		Square bales to field edge - tarping	Automatic stacker, telehandler
COUNTRY SIDE	Transport	Hauling round bales	Truck trailer – flat bed
		Hauling square bales	Truck trailer – flat bed, container
		Hauling cubes	Truck trailer - container
		Hauling chops	Truck trailer – chop box
	Storage	Stacking and storing round bales	Shed without wall, telehandler
		Stacking and storing square bales	Shed without wall, telehandler
		Unloading and storing cubes	Fat storage with wall, front-end loader
		Unloading chops	Flat storage with wall, front end loader
	Shredding and drying	Grinding round bale	Tub grinder
		Grinding square bales	Square bale shredder
		Drying	Pneumatic drying – rotary drum or fluidized dryer
		Cubing or briquetting	Cuber, bricquetter, hydrothermal conditioning
		Cube conditioning and cooling	Cube cooler
		High density bales	Hydraulic double compaction
REFINERY	Transport	Receiving and stacking round bales	Truck, telehandler, flat storage without walls
		Receiving and stacking square bales	Truck, telehandler, flat storage without walls
		Receiving and storing cubes	Truck, pit, elevator, distribution, cylindrical bin
	Reclaiming	Reclaiming and preparing round bales	Telehandler, tub grinder, conveyor belt

		Reclaiming and preparing square bales	Telehandler, square bale shredder, conveyor belt
		Reclaiming and preparing cubes	Gravity self unloader conveyor

The research also indicates that moisture controlling, densification, and system modeling are necessary for biomass supply chain optimization. Moisture controlling plays an important role in biomass material storage. High moisture content results in material loss from fermentation during storage. Rentizelas et al. (2009) suggest that storing biomass material in plastic wrap on the field is the most economically effective storage practice. It is also found that the moisture content of the biomass material affects the pelletizing process, which may precede the energy conversion process. A too high or too low moisture content results in lower throughput of the pelletizing process. Before it is used in the energy conversion process, biomass needs to be ground and may be palletized into a proper shape and size (Mani et al., 2004; Sokhansanj & Turhollow, 2004). Moreover, densification of the biomass material increases bulk density and results in easier handling and transporting performance.

2.3.2 Biomass transportation

To deliver biomass to a pelletizing or other preprocessing plant, the material is first harvested from the field and delivered to the plant by using a selected transporter. Hay-type biomass will be densely packed into bales and will be loaded and unloaded with a mobile forklift machine, while particle-type biomass will be loaded and unloaded directly to the truck using a mobile wheel loader machine (Kumar & Sokhansanj, 2007). Temporary storage could be located on the field to reduce transportation distance (Ravula et al., 2008a). The estimated costs for transportation were investigated by Duffy (2008).

Perlack and Turhollow (2003) conducted an evaluation of the cost for collecting, handling, and hauling corn stover. As a larger area is required to support a larger facility, increased transportation costs result. In the study, different types of transportation trucks were tested with different facility sizes. Results showed that a tractor-wagon has better performance for a facility size of 500 dry tons day^{-1}; but as the facility size increases to 4000 dry tons day^{-1}, transportation costs of the tractor-wagon and truck (flatbed trailer) are approximately the same. The results are shown in **Figure 2.3.** Different biomass availability, determined by yield and density of corn cultivation, were also tested for different facility sizes. Three levels of biomass availability (low availability, base case, and high availability) resulted in a large gap in delivery cost per ton of biomass feedstock as shown in **Figure 2.4.**

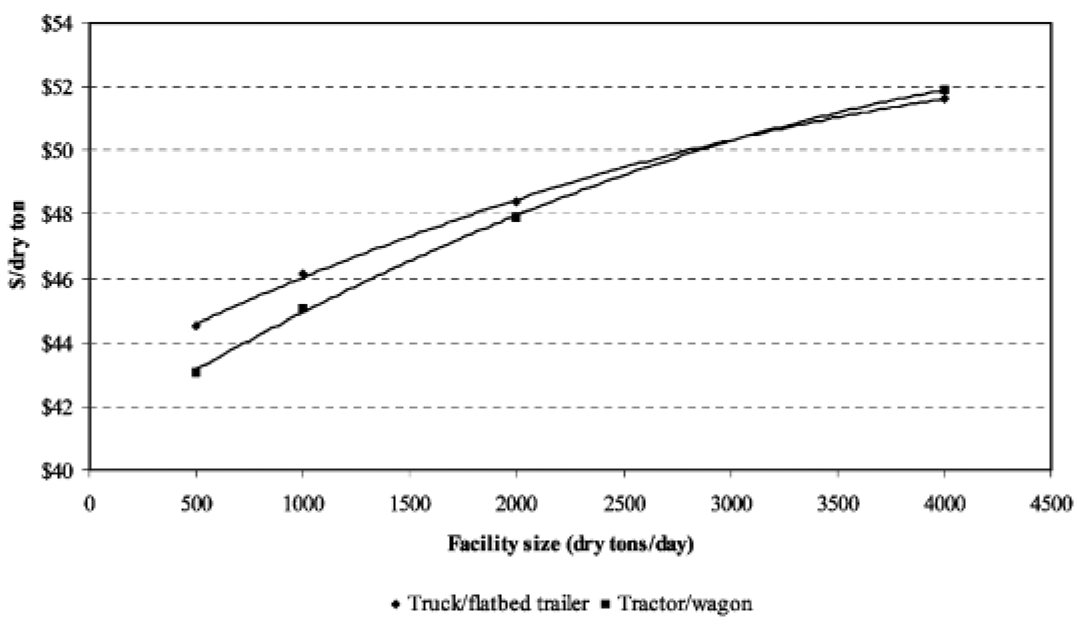

Figure 2.3 Stover delivery costs under two alternative options for hauling from the field to storage (Perlack & Turhollow, 2003)

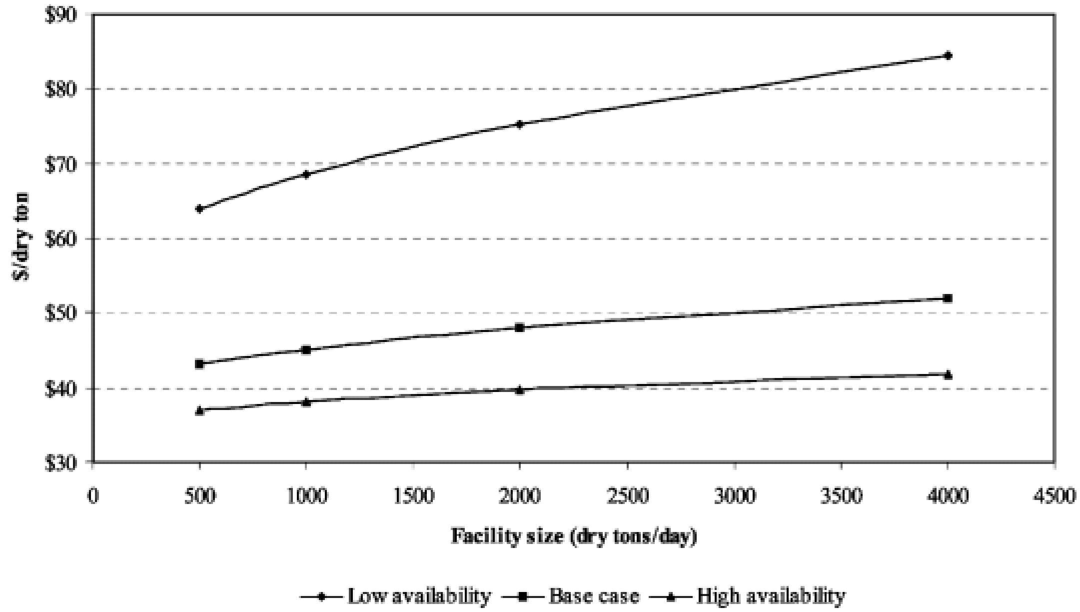

Figure 2.4 Variation in delivery costs under low and high resource availability (Perlack & Turhollow, 2003)

2.3.3 Grinding and densification

Biomass densification is a necessary step that must take place before biomass can be either used as a heating source in a coal-based power plant or as the seed material for conversion into biofuels. Variable factors such as material characteristics, temperature, moisture content, feed rate, particle size, and pelletizing pressure are responsible for the variability of cost and power requirement (Sokhansanj et al., 2003). Binding characteristics of a particular biomass also affect the pelletized biomass product such as hardness and bulk density. A pre-heating process is sometimes used either to reduce moisture content or to help the binding process of the biomass particle. *Show Me Energy*, a pelletizing plant in Centerview, MO, uses a hammer mill for heating and cohering biomass texture, because of mixed biomass material types. There is rarely research on multi-biomass pelletization/densification which could be due to the uncertain characteristics of mixed biomass particles such as particle size and binding ability.

Biomass material is delivered to the pelletizing plant as bales or chopped material. The large materials will be ground into smaller sizes ranging from 0.8 to 3.2 mm before being pelletized. Grinding performance in terms of cost, ground material size, and the material physical properties were studied by Sokhansanj and Turhollow (2004). Before grinding, the original loose plant-based biomass has its bulk density ranging from 50 to 130 kg m^{-3}. Grinding and pelletizing operations increase the material bulk density range from 120 to 500 kg m^{-3}. Wheat, barley straw, corn stover, and switchgrass are ground to three different sizes with two levels of moisture content. Cost and energy consumption are measured for each scenario. Mani et al. (2004) estimated the cost for a cubing operation of corn stover. The capital cost related to the densification process is also identified and included in the research.

2.4 Supply chains

The supply chain is defined as a system composed of suppliers, manufacturers, distributors, retailers, and customers, where information sharing inside the system happens in both directions. Each unit inside the system will attempt to optimize its own performance independently. However, all units are interconnected and thus, optimization of the whole supply chain needs coordination by each party in the system.

The bullwhip effect, described as growing variation upstream in a supply chain, will result in lower performance of the system. The bullwhip effect is a result of uncertainty inside the system. Information asymmetry, demand forecasting, lead-time, batch ordering, supply shortages and price variations are identified as possible causes of the bullwhip effect (Fiala, 2004). Expected benefits from applying supply chain management include decreased inventory costs, reduced flow time, and better matching of supply and demand (Croson and Donohue, 2002).

Synchronizing information inside a supply chain to improve the supply chain performance is presented in work by Kok (2005). *Philips Electronics* is used as study case in this research. To stay competitive in the current market, optimization needs to be expanding to the supply chain level. In this project, Philips Electronics aims to increase cutover-service levels and reduce inventory by synchronizing the whole system together. Full collaboration of information and decision making among all parties is implemented in the system. For planning and scheduling, statistical data are combined with stochastic models to predict the probability and trend of demand.

Another goal in supply chain management is to improve material flow throughout the system. Using storage as a material buffer is the simplest method to prevent insufficiency of material but increase large amounts of cost. Higher uncertainties in demand result in higher amounts of stock material in the inventory.

Lee and Chu (2003) studied on inventory management in a two-member supply chain, a vender and a retailer. Traditional inventory management, in which the downstream retailer controls the inventory level and safety stock level, is compared with a new scenario, in which all inventory management responsibilities belong to the vendor. The two scenarios are analyzed in the newsboy environment. Expected payoffs from both cases are calculated and compared by using a mathematical model. It is suggested that the vender will be interested in controlling the inventory level when the upstream vender needs to control a larger stock level than what the downstream wants.

Gjerdrum et al. (1999) employed a mathematical programming formulation for fair profit distribution between each level in a multi-enterprise supply chain. Optimization of the overall supply chain normally leads to unsatisfactory profit distribution among the members. Two different enterprises are tested with mixed integer non-linear programming (MINLP) by applying the Branch-and-Bound algorithm. The computational result shows very close profit compared with the regular optimization but much more equally distributed profit inside the supply chain, which is desirable in terms of viability and stability of the whole system.

Johnson (2004) observed a roundtable discussion hosted by Dartmouth's Tuck School of Business and summarized important issues in supply chain management into five areas: *globalization and outsourcing*, *new information technologies*, *economic forces*, *risk management*, *and product life-cycle*. These problems are the result of market changes. Increasing global competition and complexity in supply chain leads to *globalization and outsourcing*. Productions are allocated throughout the world to support the local customer. Improvement of *information technologies* is also a factor that allows implementation of a communication network inside a supply chain. Stochastic models and distributions are used to estimate probability which could be used in the negotiation of price and contract between producers and suppliers. High competition also leads to *Short life-cycle* of product in the current market. *Risk management* and forecasting of trend can be done through statistical analysis.

2.5 Biomass logistics modeling

System modeling has been used to study biomass utilization systems and it plays an important role in system optimization because of the complexity of the biomass supply chain system. Several studies have been done, but most research work focuses on specific parts of the system.

Fiala (2004) emphasizes the important of computer modeling and information sharing in supply chain by creating a model using STELLA, computer software capable of simulating a dynamic system. Suppliers, manufacturers, distributors, retailers, and customers are made to respond differently to a certain event occurring in the system. The model is tested between cooperative and non-cooperative decision making.

A geographic Information System (GIS) based model has been developed by Graham et al. (2000) to estimate potential biomass cost and suppliers across an area. In this study, delivery cost of switchgrass was studied in eleven states. Estimation of supplier delivery price is based on available land for biomass crop cultivation, spatial variability in biomass crop yield, collection cost, and transportation cost. The model also helps identify a potential location for the energy conversion plant. Data from digital maps were used to estimate the required land and farmgate price of the biomass feedstock based on yield and land type. This information was then combined to calculate delivered feedstock cost as well as a potential site for facilities. The capacities of 100,000 tons and 630,000 tons were tested to show the differences in marginal cost of the delivered supplies.

Gallagher et al. (2003) presented an economical model to estimate cost and supply of biomass residue in four regions inside the U.S.: the corn belt, the great plains, the west coast, and the south. Yield of biomass was used as the key variable determining the cultivation area and the average transportation distance between the pickup location and the processing plant. This study looked at: corn, wheat, sorghum, barley, oats, and rice. Cost and supply of delivered biomass in the area were estimated based on economical factors, environmental factors, and biomass crop characteristics. Input costs for operations were also identified in this research work.

An important modeling effort by Sokhansanj et al. (2006) resulted in the integrated biomass supply analysis and logistics (IBSAL) simulation model programmed in ExtendSim, an object-oriented simulation platform. The model simulates collection, storage, and transportation of biomass material to biorefinery. The overall structure of IBSAL simulation model is presented in **Figure 2.5**.

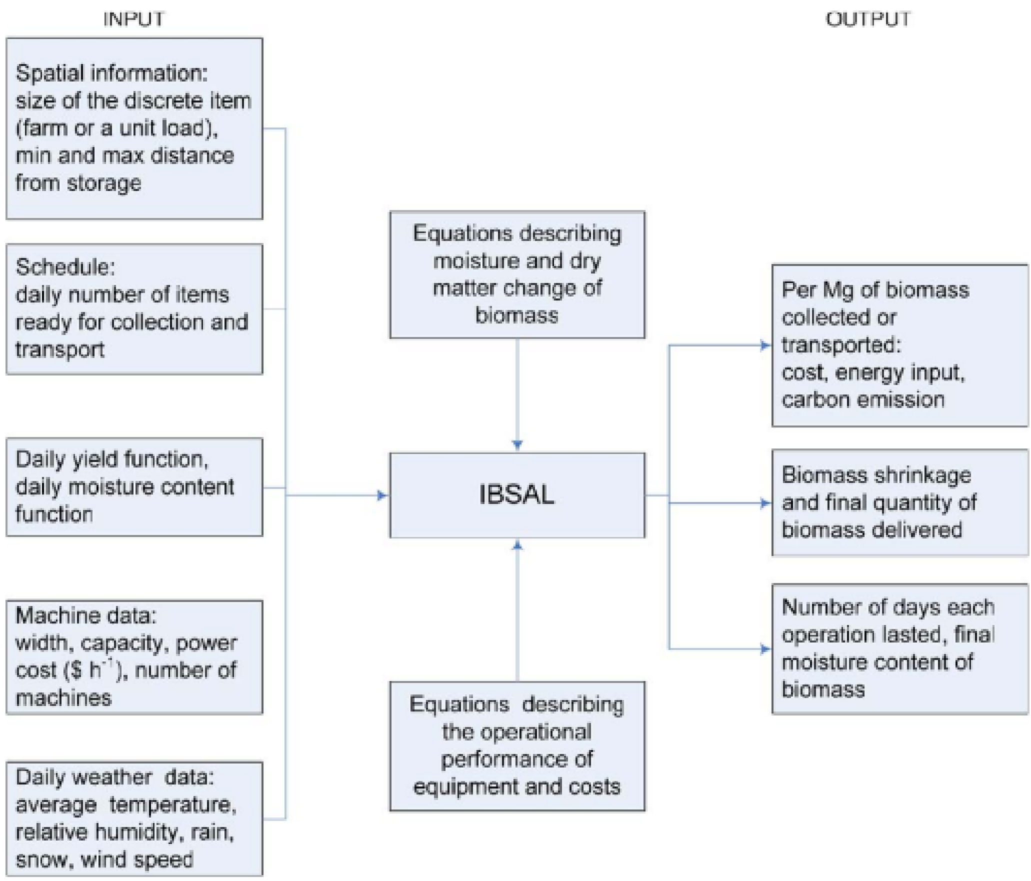

Figure 2.5 Overall structure of IBSAL collection modules defining input and output (Sokhansanj et al., 2006)

The IBSAL model estimates the amount of delivered biomass material through time. Cost and energy input analysis is based on operations required to deliver biomass materials to the processing plant. Corn stover is used as a study material in the simulation to predict the delivery cost after collection. The effect of moisture content and material lost from fermentation and the processing machine are also included to increase the accuracy of the simulation. IBSAL provides an overall picture for cost estimation and energy usage estimation in biomass material collection and transportation; however, it does not include cultivation and densification operations, which also lead to cost and energy input to the biomass utilization system.

Switchgrass is studied by using the IBSAL model (Kumar & Sokhansanj, 2007). A variety of collection methods and handling methods are simulated in the model to find the optimal scenario for switchgrass material. In the simulation, three biomass collection systems (baling, loafing, and ensiling) are evaluated by using different handling methods such as loading and unloading machines. A total of seven collection and handling scenarios are simulated with nine different plant capacities. The simulation results suggest that collecting switchgrass as loaf and grinding in the field with a mobile grinder before transporting to the processing plant is the most economical. Collecting switchgrass into square bales and it is subsequently grinding it on the field before transportation to the processing plant has the lowest emission rate.

While IBSAL is used to optimize a system in terms of process selections, there is also interest in simulation models to study transportation performance of different truck policies. Sigma, a discrete-event simulation software environment, was used to simulate the cotton gin logistics, which has similar characteristics to biomass logistics (Ravula et al., 2008a). The original truck policy, which is a first-in, first-out policy where trucks randomly pick up cotton gin from the field, is simulated to validate the model. Later, three new policies are simulated: shortest first, longest first, and longest first/shortest second (LFSS). Simulation results show that the LFSS truck policy improves the consistency of material flow which improves the utilization rate of trucks and collecting machines. Another truck policy has been studied, where the simulation of the LFSS truck policy is compared with the Sector-Based Loader Assignment (SLA) truck policy

(Ravula et al., 2008b). The simulation included four satellite storage locations (SSLs) which were located in fields and used as temporary storage before delivering collected biomass material to the processing plant. To reduce the problem of crisscrossing, the travel Salesman Problem algorithm is applied in the LFSS truck policy. Mobile loaders work with trucks to transport material to SSLs. In the second policy of sector-based loader assignment, the whole area is divided into five regions. Loaders run in a circle from each pick-up location to load biomass material to trucks for delivering to the SSLs. A comparison between the two policies shows that the LFSS policy has a lower maximum number of trucks and a lower average inventory level. Even though the travel distance is greater, LFSS is more economical, as fewer trucks are needed.

Collection and storage simulation models for cotton stalks and almond tree pruning were developed in a study by Rentizelas et al. (2009). Cotton stalks and almond tree pruning, which share similar characteristics with biomass crops, are used as a base model to optimize biomass collection and storage systems. Different storage scenarios -- warehouse with biomass drying capability, regular warehouse, and plastic-wrap in field--are simulated to see the difference in cost and effect. Results show that cost reduction from storing biomass in plastic wrap exceeds the opportunity cost from biomass material lost during storage.

Petrolia (2008) presents a different method to estimate transportation cost for corn stover residue. Probability distribution of costs under different assumptions was estimated by Monte Carlo simulation. Four scenarios were created from a combination of tillage policies and collection methods. Costs involved in cultivation and transportation were investigated and simulated based on settings from each scenario. The simulation results show a range of possible costs and estimated weights.

CHAPTER 3

MODEL DEVELOPMENT AND VERIFICATION

3.1 System structure and characteristics

A biomass utilization system model is developed based on the operations of *Show Me Energy*, a biomass pelletizing plant located in Centerview, MO. Biomass material is collected from surrounding areas and pelletized. The plant is located where a variety of biomass materials are produced. The plant is in the *Corn Belt,* where there is abundant corn cultivation. Fescue grass seed production and lumber industry, which are sources of seed hull and sawdust, are also located in the surrounding area.

Similar to the supply chain structure (Kumar & Sokhandanj, 2007), the biomass utilization system consists of three sub-operations; material production, handling and transportation, and processing, connected in a sequential order (Sokhansanj et al., 2003). The biomass utilization system model is developed to be capable of studying several aspects in the supply chain management system, including material flow, inventory level, hauling distance, and trucking hours.

Material production is a cultivation process, which results in the availability of biomass material at a specified point in time. Available biomass materials will then be harvested, stored, and transported in the handling and transportation operations. The biomass material is delivered to the plant in discrete amounts and is processed by the plant in the processing operation. Material production, and handling and logistics sub-models are developed based on data from published literature, while the actual data from *Show Me Energy* is used for the processing plant sub-model. Input and output of each operation in the biomass utilization system model are presented in **Figure 3.1**.

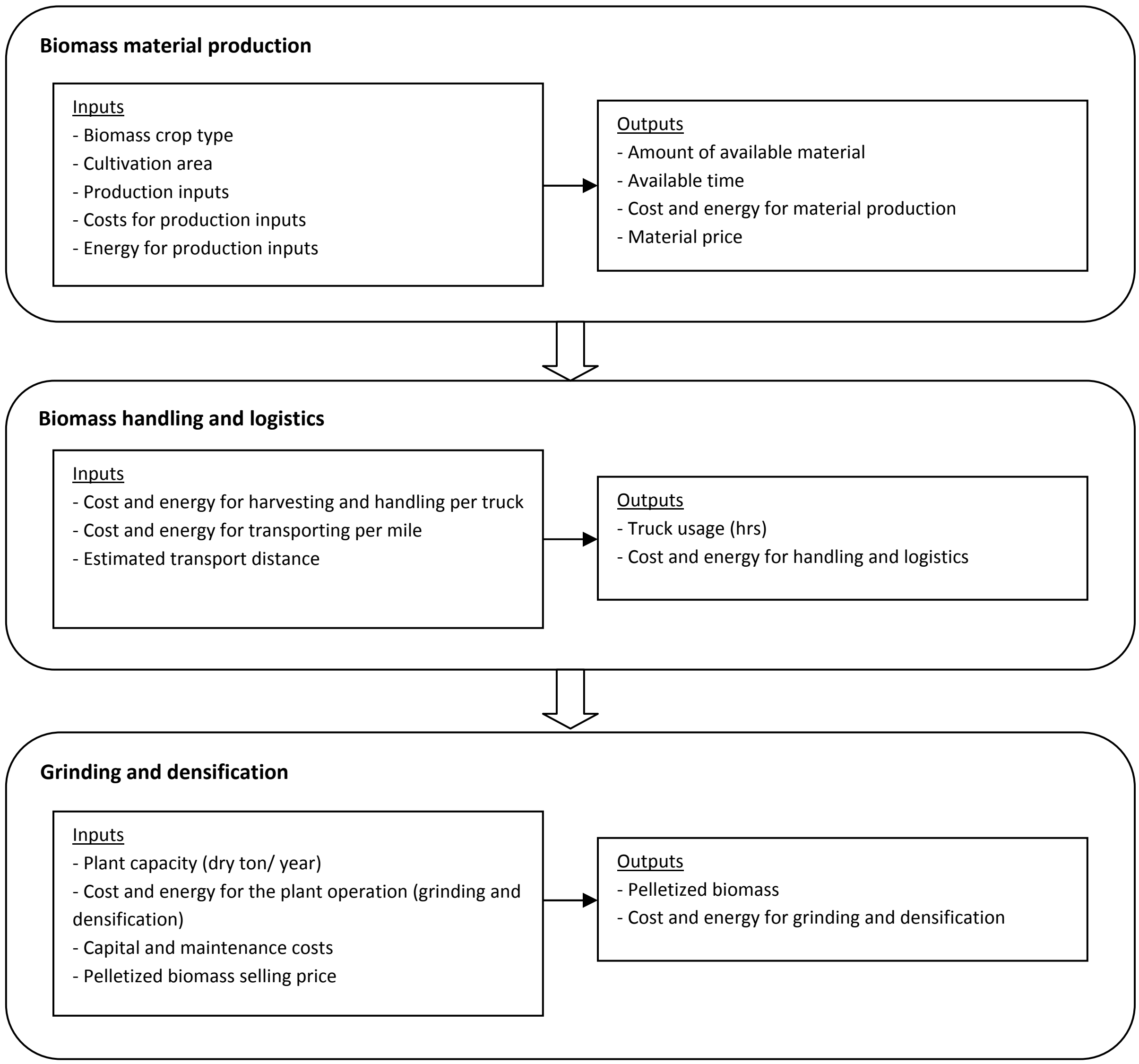

Figure 3.1 System sub-models with inputs and outputs

The net benefit for each party in the supply chain, and the energy balance of the whole system are analyzed for economic viability and energy sustainability. Different selections of operations and policies lead to a variety of inputs and system configurations. Data and structure are adjusted to match with the characteristics of given scenarios.

3.1.1 Biomass material production

Biomass material production can be categorized by *biomass crop cultivation* and *biomass residue production*. Biomass crops are cultivated to produce a biomass material supply. Crop species used in *biomass crop cultivation* are selected based on high energy return per unit area, or are generally identified as high-yield biomass material. Although there are some variations in material composition between different crop types, they are estimated to have the same amount of energy output per dry ton of material. Dry ton yield (dry tons ha^{-1}) is then used as an index to identify energy production performance for each biomass crop. In this study, switchgrass and miscanthus are selected to be studied because of their high potential as biomass crops (Mclaughlin & Kszos, 2005; Kumar & Sokhansanj, 2007). *Biomass residue production* is a gathering process of leftover biomass material from row crop cultivation or industrial activity. Examples of residue from row crop cultivation are corn stover, seed hull, and soybean stems and leaves. In general, the residue from row crop cultivation will be left on the field after grain harvesting as a natural fertilizer for land preservation. Gathering of these residues may reduce the soil nutrition level. Without extra fertilizer, this may lead to low soil quality after many years of residue collection. As such, effective management is required for sustainable and long-term use of the land. Residues from industrial activities are alternative sources of biomass material. Disposing of residue from industrial activity usually costs money to the producer; selling the residue as biomass feedstock is a good solution to dispose of the residue. Sawdust, the residue from the lumber industry, is an example that we use in this study. Two type of biomass materials and production methods are shown in **Figure 3.2**.

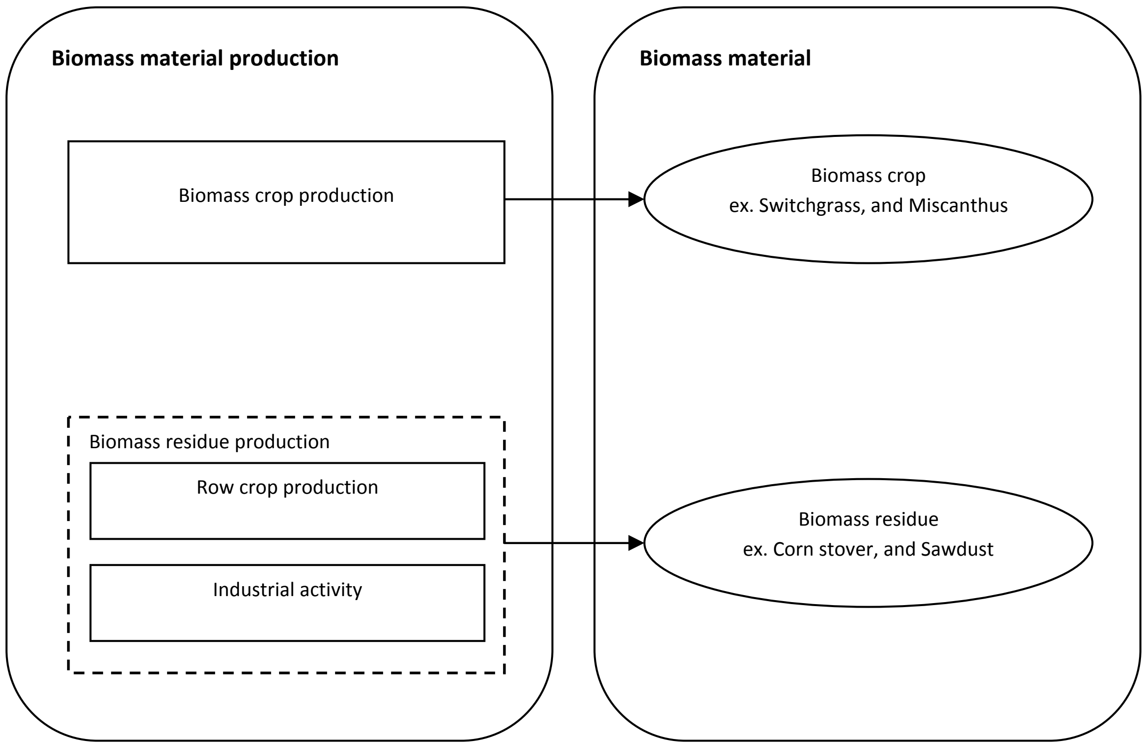

Figure 3.2 Biomass material production

Biomass material production locations normally surround the processing plant in a circular shape. As shown by Ravula et al. (2008a)**,** this is done to minimize the average transport distance from the plant to any point in the area for picking up biomass material. Research by Gallagher et al. (2003) and Sokhansanj et al., (2006), the total area surrounding the biomass processing plant is identified as the biomass material production field owned by a single owner or by multiple producers willing to cooperate and supply their biomass material to the plant.

Moreover, there will be no other types of land usage apart from biomass material production. This is unpractical given the current practice and the original goal of Biomass Research and Development Technical Advisory Committee (DOE, 2003), aiming to get participation from local biomass material producers to increase the income of local farmers in the area. In this study, we assume that various biomass materials are available in the area and that producers may or may not supply material to the plant. In addition, some of the land might be used for other activities such as housing or manufacturing. This was done in work by Power et al., (2008) and Huang et al. (2009). Indeed, it is more practical to assume that some proportion of land will not be used for biomass material production, and that several types of biomass material will be present for collection in the area surrounding the plant.

The time at which materials are available after cultivation of *biomass crop* and *biomass crop residue* is another issue in this biomass utilization system. Annual crop cultivation in the Mid-West area ranges from late spring to late summer. Different types of biomass crops vary in their available time of biomass material based on maturity time (Power et al., 2008 and Rentizelas et al., 2009). Since cultivation of *biomass crop* and *biomass crops residue* can be done in a yearly cycle, producing large amount of biomass material and storing it for later use is essential for sufficient material supply after losses from fermentation during storage (Shinners et al., 2007).

Moisture content is a major factor controlling the fermentation rate of biomass material. Combined with long storage periods, it leads to a high loss of biomass material. Biomass, after being collected, is then stored in plastic wrap as it is suggested that wrapping biomass material in a plastic sheets is the most efficient way to store biomass material (Rentizelas et al., 2009).

Different from yearly production of crops residue from manufacturing activities are typically generated in a constant rate year around. This characteristic reduces costs of storage, since material can be directly fed to the system without the need for large material buffer storage.

Available material from biomass crop and biomass crop residue was calculated based on two factors: the estimated yield and the cultivation land size. Because a variety of crops are present randomly around the plant, five distance ranges were used to differentiate the material production annulets. This allowed each annulet to have its own cultivation land density for each biomass crop, different biomass material price, and different random distribution for transport distance estimation. For example, the soil within the annulet five could have different properties from those of the one close to the plant and that could lead to an increased cost for land preservation and higher price of biomass material. Thus, there would be fewer numbers of farmers participating in annulet five, which could be represented by lower density of biomass crop cultivation. Although biomass residue from industrial activities was not related to land usage for production, five distance ranges were used for the estimation of transport distances.

Biomass residues do not take any type of input since they are actually waste products. On the other hand, biomass crop cultivation needs investment and energy as inputs. Crop cultivation is a sequence of three sub-operations, including land preparation, planting, and irrigation and chemical application (West & Marland, 2002). Each operation takes inputs which either adds cost or energy to the system. Disks and plows are used in land preparation before planting can take place. After planting, fertilizer, herbicide, pesticide and irrigation are applied to the cultivation field from time to time based on the different needs of each biomass crop. Cost and energy usage of each unit input are listed in **Table 3.1**. Work by Duffy (2008), and that by Pimentel and Patzek (2005) estimated price and energy used for production per input unit. Price of diesel and gasoline per gallon were taken from the current market prices as of May 30, 2009.

Table 3.1 – Cost and energy per input unit in cultivation

	Price ($/unit)	Energy (MJ/unit)	Emission (kg C/unit)
Switchgrass Seed (kg)	16.5[a]	43.5[b]	0.86[b]
Miscanthus Seed (kg)	16.5[a]	43.5[b]	0.86[b]
Nitrogen (kg)	0.682[a]	57.46[b]	0.8575[b]
Phosphorus (kg)	0.814[a]	7.08[b]	0.1651[b]
Potassium (kg)	0.506[a]	6.05[b]	0.1203[b]
Lime (kg)	0.021[a]	1.71[b]	0.0357[b]
Herbicide (kg)	20[d]	266.53[b]	4.7024[b]
Insecticide (kg)	20[d]	284.82[b]	4.932[b]
irrigation (ha-cm)	15.185[d]	0.0926[b]	5.251[b]
Electricity (kWh)	0.07[e]	3.6[c]	0.18[b]
Diesel (Gallon)	2.29[f]	146.238[c]	0.02195[b]
Gasoline (Gallon)	1.8[f]	131.794[c]	0.02127[b]
Manpower (hr)	14[g]	0	0

a Duffy (2008). Miscanthus is assumed to be similar to switchgrass
b West & Marland (2002), Miscanthus is assumed to be similar to switchgrass
c Transportation energy book, table B.4
d Pimentel & Patzek (2005)
e Energy Information Administration (US government), data as of May 2009
f Market price as of May 2009
g Show Me Energy, as of January 2009

To compute the total cultivation cost and energy, the cultivation area and the amount of inputs per land unit (ha^{-1}) must be specified. Input information was gathered from published documents or actual use from local farmers in the Mid-West area. Estimated inputs for production (per area unit) of five biomass materials are presented in **Table 3.2**.

Table 3.2 – Input required per land unit of each crop type (Show Me Energy, 2009)

	Corn Stover	Saw dust	Seed waste	Switchgrass [c]	Miscanthus [c]
Land ($ ha^{-1})	0	0	0	80	80
Moisture Content (%)	15 [a]	9 [a]	6 [a]	15	10
Yield (dry Mg ha^{-1})	5.7 [a]	-	0.5 [a]	13.526	25.81
Seed (kg ha^{-1})	0	0	0	11.23	11.23
Nitrogen (kg ha^{-1}) [b]	0	0	0	84	84
Phosphorus (kg ha^{-1}) [b]	0	0	0	33.7	33.7
Potassium (kg ha^{-1}) [b]	0	0	0	45	45
Lime (kg ha^{-1})	0	0	0	3,000	3,000
Herbicide (kg ha^{-1})	0	0	0	0	0
Insecticide (kg ha^{-1})	0	0	0	0	0
irrigation (cm ha^{-1})	0	0	0	0	0
Electricity (kWh ha^{-1})	0	0	0	0	0
Diesel (Gallon ha^{-1})	0	0	0	12.4	0
Gasoline (Gallon ha^{-1})	0	0	0	7.4	7.4
Manpower (hr ha^{-1})	0	0	0	9.9	8.4

a *Show Me Energy Coop.* data provided as of December 2008
b Duffy (2008). Miscanthus is assumed to be similar to switchgrass
c *Flick Seed Company*, data provided as of February 2009

3.1.2 Biomass handling and logistics

Handling and transportation operations control the flow of biomass supply from a biomass material production site to a processing plant. Three operations of handling and transportation, are harvesting or gathering, loading/unloading, and hauling (Kumar & Sokhansanj, 2007). Biomass material will be available for collecting at either a cultivation field or a manufacturing plant. There is no need to harvest biomass residue from manufacturing, since it can be directly loaded from storage to a truck. However, biomass material from a crop needs to be harvested from the field and prepared for transportation to the processing plant. Mostly, biomass crops will be available for harvesting once a year between early summer and late fall. For some biomass crops, such as switchgrass, harvesting can be done twice a year depending on yield and the maturity of the crop. But to simplify the process, it was assumed that each biomass crop would be harvested only once a year. Each biomass type requires a different harvesting and handling method (Kumar & Sokhansanj, 2007). Material is harvested by chopping it down into small pieces, or by packing it together into round or square bales on the field, and then storing it in local storage before loading to a carrier. Chopped biomass is loaded to the carrier with front wheel loaders while baled biomass is loaded with forklifts.

Material will be delivered to the plant by using trucks as carriers. Time required for one delivery consists of loading time, travel time, and unloading time. Loading and unloading times are a function of material amount and machine loading/unloading speed, while travel time is a function of distance and truck speed. The average speed for trucks was estimated at 65 miles hour^{-1} based on data from local truck drivers while the estimated travel distances were given from biomass material producer records. At the point of arrival, biomass material was loaded to material storage, separated by the biomass material type.

Truck size varies based on truck management policy. It is a key factor affecting cost and energy input for handling and transportation operations. Increasing truck size reduces average energy spent in transporting biomass material. As suggested by Duffy (2008), a 22-ton semi truck is the most suitable truck size for biomass transportation. However, local biomass producers will have no interests in purchasing or owning such large-sized trucks because of low truck utilization. As such, there are two suitable options for truck management policies. For the first policy, the material producer's truck is used to transport biomass material to the plant. Truck size may vary depending on the material producer's preference. Delivered biomass price is based on transportation distance between the loading location and the processing plant. In this policy, the processing plant will not get involved in any part of the transportation. In the second policy, the plant will either own the truck or hire a third party to deliver the biomass (Duffy, 2008). In this second policy, the truck size will be 22-ton, which is more economical and energy-effective. Biomass material price will be at the farm gate price but the processing plant will be responsible for the cost of truck operation.

The cost and energy consumption for operations of handling and transportation are either distance-dependent or distance-independent as pointed out from Kumar and Sokhansanj (2007) and Duffy (2008). Distance-independent operations are loading and unloading activities whose cost and energy use do not depend on the location of the material producer. An example distance-dependent operation is hauling whose cost and energy input is a direct function of the distance between the plant and the material pickup location. Input data for cost and energy consumption of handling and transportation are show in **Tables 3.3** and **3.4**, respectively.

Table 3.3 – Cost for handling and transportation for semi truck

	Corn Stover	Saw dust	Seed waste	Switchgrass	Miscanthus
Loading & collecting (\$ truck^{-1}) [a]	291.15	30.10	30.10	291.15	291.15
Unloading (\$ truck^{-1}) [a]	27.3	27.3	27.3	27.3	27.3
Loading time (hr truck^{-1}) [b]	0.5	0.5	0.5	0.5	0.5
Unloading time (hr truck^{-1}) [b]	0.33	0.33	0.33	0.33	0.33
Man-hrs (\$ day^{-1}) [c]	360	360	360	360	360
Truck cost (\$ day^{-1}) [b]	1,680	1,680	1,680	1,680	1,680
Speed (mph) [c]	65	65	65	65	65
Distance-dependent cost (\$ mile^{-1}) [d]	0.42	0.42	0.42	0.42	0.42
Transport amount (dry ton truck^{-1}) [e]	18.7	20.02	20.02	18.7	19.8

a Kumar & Sokhansanj (2007)
b Duffy (2008)
c *Show Me Energy Coop.* (2009)

d Kumar & Sokhansanj (2007), and Huang et al. (2009)
e Based on moisture content of material from *Show Me Energy* coop. (2009) and *Flick Seed Company* (2009)

Table 3.4 – Energy for handling and transportation

	Corn Stover	Sawdust	Seed waste	Switchgrass	Miscanthus
Distance-independent energy(MJ truck^{-1})[a]	3302.5	386.1	386.1	3,302.5	3,302.5
Distance-dependent energy (MJ mile^{-1})[b]	26.6	26.6	26.6	26.6	26.6

a Energy for collecting, loading, and unloading operations based on data from Duffy (2008), Sokhansanj et al., (2006), and *Show Me Energy Coop.*
b Energy input for hauling operation at 5.5 miles/gallon

3.1.3 Biomass processing plant

Show Me Energy, a biomass pelletizing plant in Centerview, MO, is used as a model biomass processing operation. Three types of biomass materials, including corn stover, sawdust, and seed waste, are delivered to the plant and stored separately in three storage areas. Corn stover and seed hull are residue from the yearly production of grain by farmers. Sawdust is residue from the operation of lumber mills and is delivered to the processing plant in a regular manner. Other hay-type materials such as switchgrass and miscanthus can also be substituted for corn stover.

The approximated storage size of hay-type material is 320 tons or 250 bales. Two other storage sizes for seed hull and sawdust are 180 tons or approximately 8 truck loads. Hay-type material can be stored outside on the field if needed; however, it is preferred that it is stored inside of protecting material to shelter it from rain or snow. The moisture content of corn stover varies between 10 and 16 percent based on environmental and storage conditions. If a corn stover bale is stored outside on the field without cover, rain or snow may dramatically increase the moisture content of the material. Seed waste and sawdust need to be stored in the storage to minimize material loss resulting from the small particle size of the materials. The average moisture content of seed waste and sawdust are 6 and 9 percent, respectively. Minimum, maximum and average moisture contents of materials are shown in **Table 3.5.**

Table 3.5 – Material average moisture contents (*Show Me Energy Coop.)*

	Hay	**Wood**	**Seed Hull**
Average	15	9%	6%
Min-Max	13-19%	4-14%	5.7-6.3%

Not only does high moisture content result in a higher fermentation rate and the amount of material lost, but it also lowers the overall performance of the palletizing plant. Excessive moisture content cause high friction between material particles, occasionally jamming the material pipe lines or machines, and potentially resulting in an emergency shutdown of the plant. In addition, machines need to be operated at a lower throughput for eliminating the excess moisture the material has.

After grinding to reduce the particle size of corn stover, the three types of material are transported with a conveyer belt and are mixed in a mixing bin, which has a capacity of 5 tons. Mixed material is then hammered in a hammer mill to further reduce particle size and to increase temperature. Material which is too dry or too wet will need longer hammering time to blend the compositions. Mixed material is then sent to pelletizing machines where the material is pelletized into cyclical shapes about 0.2 inches in diameter, and 0.6 inches long. The majority of excess moisture content is released at the pelletizing machine. The pellets, which are still at high temperature, are sent to a cooling bin and later to the product storage, which has a capacity of 400 tons. Most of the product is sold as utility biomass, which will be used to mix with coal and burnt in a coal-based power plant. Cost and energy consumption for the pelletizing process are shown in **Tables 3.6** and **3.7**.

Table 3.6 Costs and income for the pelletizing process (*Show Me Energy Coop., 2009*)

Operating cost ($)		
Utilities	$300	day^{-1}
Manhours (5 workers)	$1,800	day^{-1}
Material input cost		
Material - Farmgate Price (member price)	$5	ton^{-1}
Material - Maximum (member price)	$18	ton^{-1}
Material (non-member price)	$40.9 - 45.3	ton^{-1}
Pelletized biomass selling price	$130	ton^{-1}

Table 3.7 Energy consumption for the pelletizing processes (*Show Me Energy Coop, 2009.*)

Operating energy		
Utilities	1,320,000	MJ/day
Material energy content		
Corn stover	18,800	MJ/ton
Sawdust	15,965.3	MJ/ton
Seed hull	18,800	MJ/ton
Pelletized biomass energy content	18,170.3	MJ/ton

3.1.4 Costs

Costs involved with the pelletizing plant include capital annual fixed cost, maintenance cost, and labor. In this study, the lifetime of the plant is estimated at 15 years (Sokhansanj et al., 2006).

1. Capital annual fixed cost is the estimated annual cost of the whole capital during their life time. The calculate capital annual fixed cost is computed as (Sokhansanj et al., 2006; ASAE, 2004):

$$R = \left[P - \frac{S}{(1+i)^n}\right]\frac{i(1+i)^n}{(1+i)^n - 1} + Pk + \frac{Si}{(1+i)^n}$$

where R = Annual fixed cost ($)
P = Purchase price of equipment ($)
i = Annual interest rate (fraction decimal)
k = Sum of rates for taxes, housing (shelter), insurance (fraction decimal)
S = Salvage value ($)

Interest rate is estimated at 8% from 10+ years maturity U.S. corporate debt reported by Merrill Lynch as of April 29, 2009. Sum of insurance, housing, and taxing is suggested at 0.02 by ASAE (2004). The salvage value can be calculated from the following equation (Sokhansanj et al., 2006; ASAE, 2004):

$$S = (C_1 - C_2 n^{0.5} - C_3 h^{0.5})^2$$

where S = Salvage value ($)
n = Year
h = Average yearly operation (hr)
C_1, C_2, C_3 = Coefficient value

Salvage value is the value left of the capital at the end of its estimated lifetime. Variable year *n* is the estimated lifetime of the plant, which is estimated at 15 years. Average yearly operation *h* is 8544 hours, since the plant is assumed to operate 24 hours a day for a whole year. Coefficient C_1, C_2, and C_3 equal to 0.943, 0.11, and 0, respectively (Sokhansanj et al., 2006; ASAE, 2004).

2. Maintenance – Repair and maintenance costs are estimated based on information given by the pelletizing plant. For each ton of pelletized biomass ton sold at $130, it is estimated that $5 is used for repair and maintenance of the plant.

3. Labor – To operate the pelletizing plant, technicians are needed in at the control room to monitor the material flow and machine status. Two workers are responsible for material loading, while another person and a foreman will help around the plant as needed. The average wage is \$15 hour^{-1}.

3.2 Model implementation

A logistic model of the biomass utilization system is a simulation model of the biomass supply chain system. It was developed in ExtendSim (ImagineThat, San Jose, CA, 2007), which is an object-oriented simulation software package. The model contains three sub-models including a material production model, handling and transportation models, and a processing plant model. Discrete rate modeling and discrete event modeling techniques are used in this biomass utilization model (ImagineThat Inc. Extend V6, 2006). In discrete event modeling, the system changes state only when triggered by an event. An item is used to represent the state of the system. The same idea applies to discrete rate modeling, but when a system is triggered by the occurrence of an event, flow changes its state. Although both modeling techniques handle different system characteristics, both of them can be combined with a flow-Item interchange and convert between flows to item.

The simulation model imitates the characteristics of the supply chain system based on data, condition, and settings. Data are stored on a spreadsheet and read by the simulation model at the beginning of each simulation run. Operations in the supply chain will be carried out as it progresses through time. System performance in terms of throughput, costs, and energy inputs are of main interests for modeling the biomass utilization system.

3.2.1 Implementation of the biomass material production model

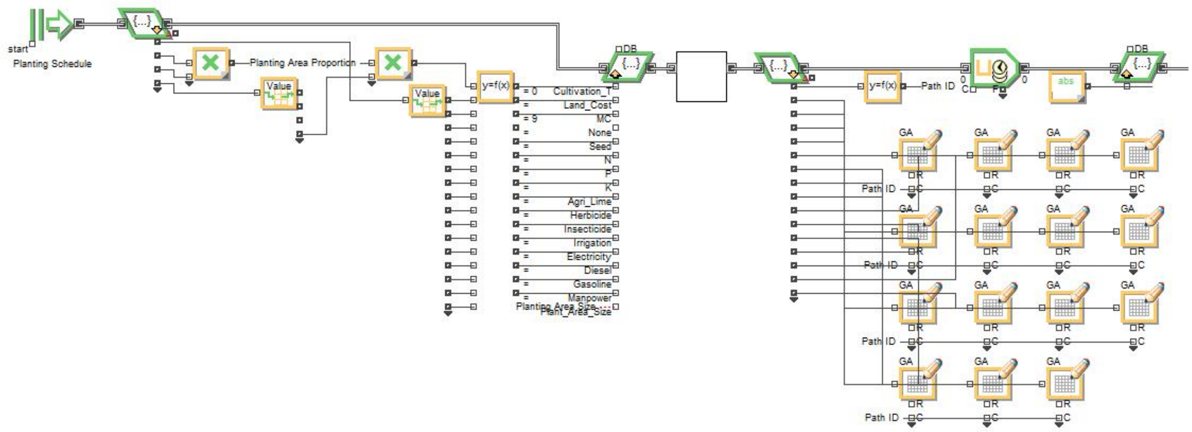

Figure 3.3 – Biomass material production simulation model

Figure 3.3 shows the biomass material production model developed in ExtendSim. Up to three types of material can be generated from the"*Planting Schedule"* block which creates items at given times. For biomass crops, each biomass crop item is generated with crop type and cultivation area attributes. These attributes are used in the *"Cultivation input/output estimation"* block to estimate the input amount for growing the selected biomass crop on the given land size. The calculation is described below:

$$Q_i = Lq_i$$

where Q_i = Quantity of input *i* (input unit)
L = Cultivation Land size (ha)
q_i = quantity of input i per hectare (input unit/ha)

Q_i is the total amount of input *i* required for cultivation in the given land size *L*, while q_i is the input per land unit given in the **Table 3.2.** Quantities of these inputs are stored as attributes in the item for later estimation of total costs and total energy inputs for the cultivation, based on the estimated cost per unit input and energy per unit input. Land size L using in the equation can be calculated from:

$$L = \pi R^2 f_a f_{lc}$$

where f_{lc} = fraction of total farm land containing crops
f_a = fraction of total farm land from which feedstock can be collected or produced
R = radius of a circular cultivation area (ha)

Land size *L* is calculated from circular area with radius *R*. f_{lc} and f_a are fraction of total land being selected for crop cultivation, and fraction of land used for local cultivation being selected for biomass cultivation. It is suggested that f_{lc} equal to 0.75 and f_a equal to 0.1, which means that 75% of land is used for crop cultivation, and that 10% of land used for crop cultivation is used for selected biomass crop. These assumptions are based on average density of crop cultivation in agricultural areas inside United Sates (Huang et. al, 2009). In this study, the values of f_a and f_{lc} can be adjusted based on assumptions and management policies.

Amount of available biomass material from crop production or crop residue is also calculated in the *"Cultivation input/output estimation"* block. The equation is expressed as:

$$M = LY$$

where *M* = biomass Material (dry ton)
Y = biomass crop yield (dry ton/ ha)

The amount of biomass material *M* is a function of the yield *Y* of crop cultivation or crop residue and land *L* used for biomass cultivation. Residue from manufacturing activity is set at a constant arriving rate with a known quantity. As mentioned earlier, costs and energy input for residue production are not included in this model, since residues are leftover materials from other activities (Gallagher et al., 2003). Each created item, which represents a biomass crop cultivation operation, will be delayed at the *"Delay for Maturity"* block (**Figure 3.4)**, which will hold each item based on maturity time of each particular crop before harvesting.

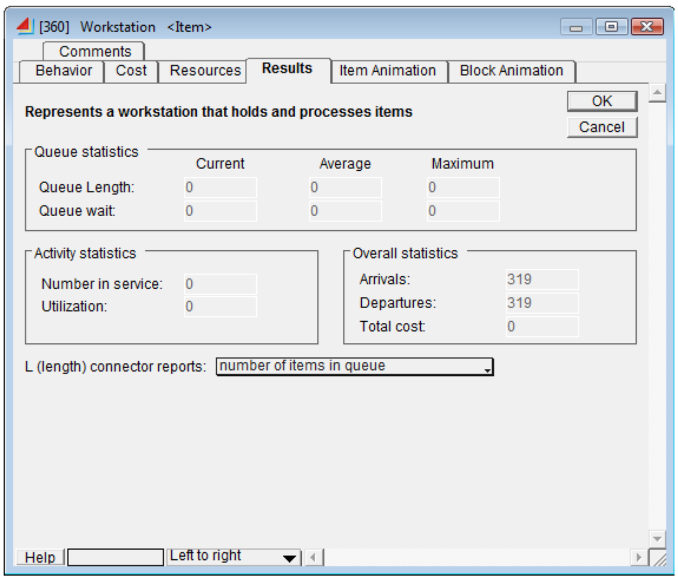

Figure 3.4 Delay for maturity block

Demand for biomass material is equal to the plant capacity. For a multi-biomass crops utilization system, the total amount of material supplying the plant is the summation of each biomass material, based on the average mixing proportion of the biomass product and the total demand of biomass material. Demand for material can be described as:

$$D = \sum M_i$$

where D = Demand of biomass material
M_i = Biomass material *i*

$$M_i = \frac{m_i D}{100}$$

where m_i = fraction of mixing proportion of biomass crop *i*

Costs and energy inputs for biomass crop production are based on crop type and land size. A list of inputs and amounts required for different biomass crop types are shown in **Tables 3.1** and **3.2**. Costs and energy inputs are calculated as described below:

$$C_c = \sum_t L c_t Q_t$$

where C_c = cost of in cultivation ($)
t = type of input
L = cultivation land size (ha)
c_t = cost of input t ($ unit^{-1})
Q_t = quantity of input t (input unit)

$$E_c = \sum_t L e_t Q_t$$

where E_c = energy input for cultivation (MJ)

L = cultivation land size (ha)
e_t = energy of input t (MJ unit^{-1})
Q_t = amount of input t (input unit)

Cost C_c and energy input E_c for cultivation are the summation of costs and energy inputs for all biomass crops. They are calculated and recorded before the item is sent out to the transportation model. Energy per input unit e_i is given in the **Table 3.1**.

3.2.2 Implementation of the biomass handling and logistics model

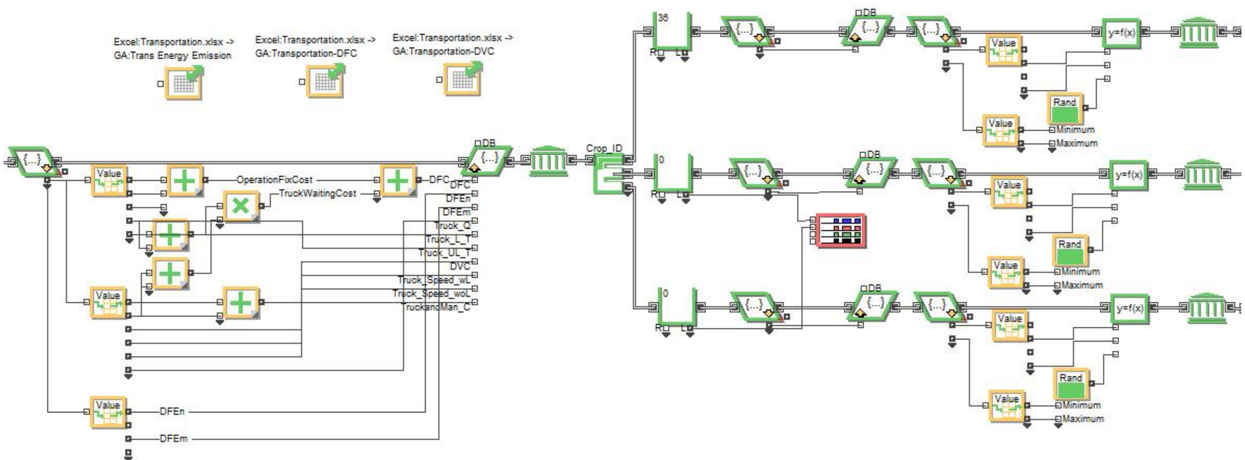

Figure 3.5 – Biomass handling and logistics simulation model

Three biomass materials are handled separately because of differences in truck size and handling methods. Estimated transportation distance between the plant and the material production site is generated by using either a random distribution function or an estimated distance equation. Selection of the distance estimation function is based on the system conditions. For the system studied, it was assumed that density of material cultivation and production was uniform in the material collection area. Therefore, the average transportation distance from any point in the circular field can be expressed as:

$$D = \frac{\beta}{\pi R^2} \int_i^R r \, 2\pi r \, dr$$

Where D = Estimated average transportation distance from any point in the circular area, accounting for non-straight roads

β = Distance factor

R = Radius of the circle and the collection location

i = Distance between the center of the circle and the location where the truck leaves to collect material

Gallagher et al. (2003) also used a similar equation to find the total transportation cost function when collecting material from any point in a circular area. It is assumed that truck starts its collection at the plant, therefore, $i = 0$, and the equation can be reduced to:

$$D = \frac{2}{3} \beta R$$

The total transportation distance for each delivery D_t is equal to the sum of the estimated transportation distances from the plant (D_c) to the field, and back to the plant (D_d), which are usually the same.

$$D_t = D_c + D_d$$

Where D_t = total transportation distance (mile)

D_c = distance from the plant to the field (mile)

D_d = delivery distance from the field back to the plant (mile)

Each item of available biomass for harvesting is stored and ready to be transported to the plant at the *"Available biomass"* block, shown in **Figure 3.6**.

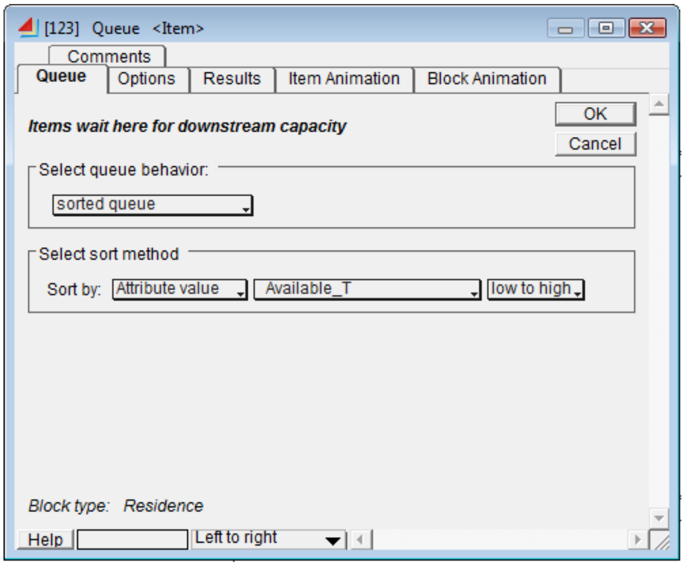

Figure 3.6. Available biomass block

Biomass material from one item will be split into several trucks using an *"interchange block"* which can convert an item to material flow or material flow to items. The image of the interchange block is shown in **Figure 3.7.**

The number of trucks in the system is determined by transportation time, which is a function of transportation distance and truck speed. However, because of the random transport distances, transport time varies, leading to uncertainty in material flow. Adjusting the number of trucks help cope with this uncertainty. When the simulation shows need for an addition truck, the number of available trucks can be adjusted in the *"Truck pool"* block shown in **Figure 3.8**.

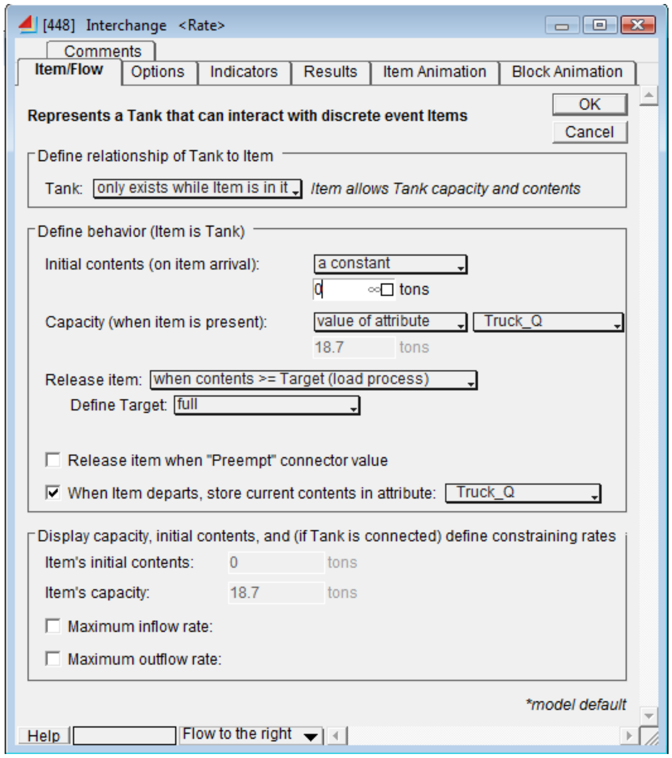

Figure 3.7 Interchange block

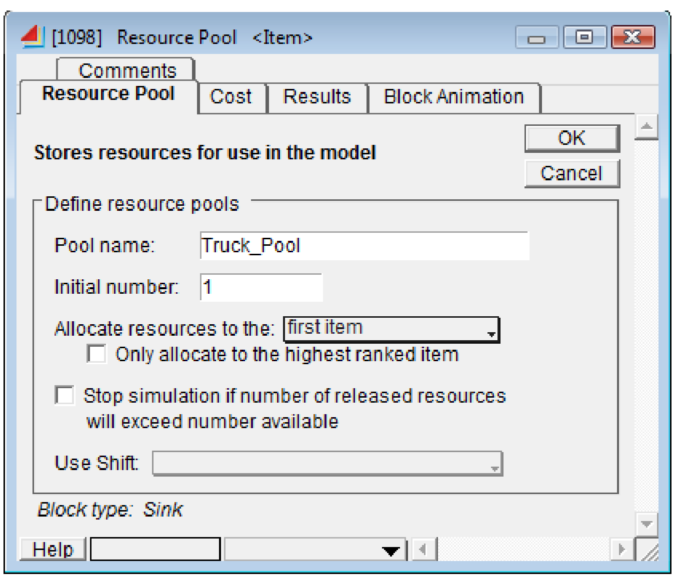

Figure 3.8 Truck resource pool

Estimated dry ton per truck for each biomass material is given because there are differences in the moisture content of the biomass materials. Available biomass from the same material type can be split or combined to fit in the truck size. As discussed by of Kumar and Sokhansanj (2007), handling and transportation systems are combinations of distance-independent operations, and distance-dependent operations. Cost and energy usage can be calculated based on the inputs to these operations.

$$C_t = DIC + DDC$$
$$= (c_l + c_u) + c_i D_t$$

where C_t = transportation cost for a delivery ($)
DIC = Distance-independent cost
DDC = Distance-dependent cost
c_l = loading cost ($/truck)
c_u = unloading cost ($/truck)
c_i = cost per mile ($/mile)
D_t = total transportation distance (mile)

$$E_t = DIE + DDE$$
$$= (e_l + e_u) + e_i D_t$$

where E_t = transport energy for a delivery (MJ)
DIE = distance-independent energy
DDE = Distance-dependent energy
e_l = loading energy (MJ/truck)
e_u = unloading energy (MJ/truck)
e_i = energy usage per mile (MJ/mile)

The cost and energy input are recorded and stored for calculating the total cost and energy usage of the whole biomass utilization system.

3.2.3 Implementation of the biomass processing plant model (pelletizing plant)

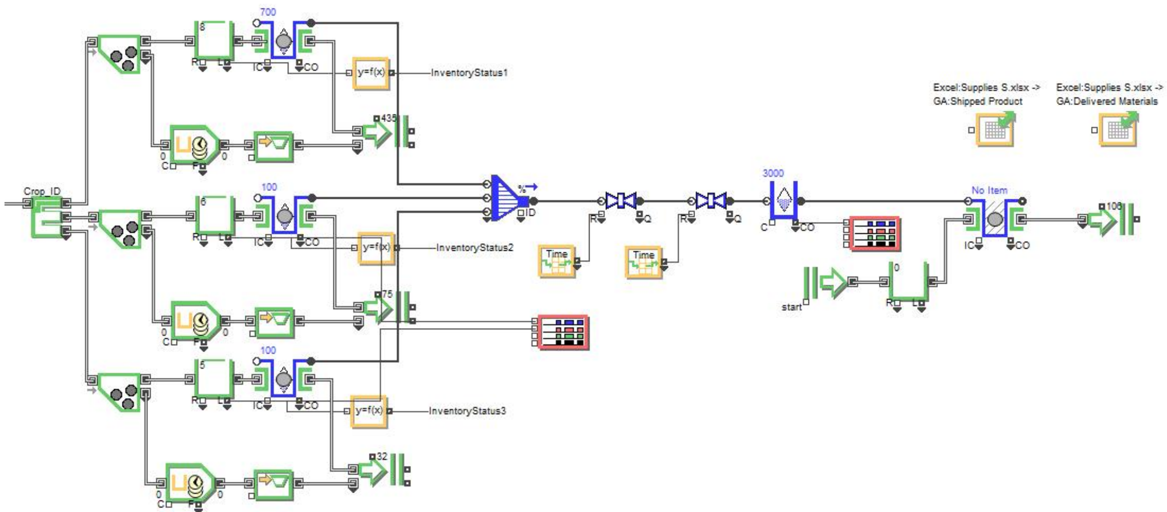

Figure 3.9 Biomass processing plant

In **Figure 3.9**, the delivery truck arrives at the biomass processing plant and unloads material into three separate storage areas. Storage size is specified and the truck cannot deliver unless there is space available for unloading the material. From the three storage areas, materials are loaded and fed to the plant at specific mixing proportions. These proportions can be adjusted if triggered by the occurrence of an event, but in this study the mixing proportions were fixed.

Due to limited information and records from the plant, the plant was built in simulation as a constraint of the material flow. The constraint represents limited throughput rate of the whole plant. Operating time of the plant can be adjusted depending on scenarios and policies. Material passing through the flow constraint is counted as pelletized material and is stored in the product storage. Product storage with the size of 420 tons, stores pelletized biomass until it is shipped out.

3.3 Model verification

The simulation model of the pelletizing plant was validated according to the system output and material flow characteristics. Records of actual delivered material and products shipped out represent the material flowing through the system. Three material storages, a pelletized biomass storage, and machine production rates represent constraints of the system.

For each truck arriving or leaving the pelletizing plant, date/time, material type, quantity, and estimated transportation distance were recorded. An example of truck record data from the plant is shown in **Table 3.8.**

In the material production model, cost and energy input from the production of each truck of material were calculated and recorded; however, there was no delay from cultivation because the model validation included only harvesting, transporting, and pelletizing biomass. Cost and energy inputs are calculated based on biomass type and quantity which were assigned to each item when created. Data used in the calculation is shown in **Tables 3.1** and **3.2.**

Table 3.8 Example records of material delivery from January 2nd to January 7th 2009 (Show Me Energy coop., 2009)

Date	Material	Ton	Crop ID	Distance ID	Dry Ton
2/1/2009	Hay	14.1	1	2	11.98
2/1/2009	Hay	4.92	1	3	4.18
2/1/2009	Hay	4.82	1	3	4.09
5/1/2009	Fiber	8.60	3	3	8.08
5/1/2009	Hay	10.55	1	5	8.96
5/1/2009	Hay	1.16	1	3	0.98
5/1/2009	Hay	8.98	1	5	7.63
6/1/2009	Hay	9.44	1	5	8.02
6/1/2009	Hay	3.24	1	2	2.75
6/1/2009	Hay	3.82	1	2	3.24
6/1/2009	Hay	9.21	1	5	7.82
6/1/2009	Hay	4.13	1	2	3.51
6/1/2009	Hay	3.96	1	2	3.36
6/1/2009	Hay	8.34	1	3	7.08
6/1/2009	Hay	7.08	1	5	6.01
6/1/2009	Hay	4.46	1	5	3.79
6/1/2009	Hay	3.85	1	2	3.27
6/1/2009	Hay	8.66	1	3	7.36
6/1/2009	Hay	6.60	1	2	5.61
6/1/2009	Hay	4.62	1	2	3.92
7/1/2009	Hay	9.26	1	5	7.87
7/1/2009	Hay	4.74	1	3	4.02
7/1/2009	Hay	0.97	1	3	0.82
7/1/2009	Hay	0.96	1	3	0.81
7/1/2009	Hay	0.92	1	3	0.78
7/1/2009	Hay	0.97	1	3	0.82
7/1/2009	Seed Waste	23.12	2	2	21.03
7/1/2009	Hay	6.60	1	2	5.61
7/1/2009	Hay	4.20	1	2	3.57

Upon arriving at the handling and transportation model, the item was sent to the pelletizing plant immediately without hauling time delay. The delay was removed because the record used in this validation included the arrival times regardless of the time required for transportation.

Cost and energy input were calculated based on truck size, transportation distance, and fuel consumption rate. The truck sizes to transport corn stover, seed hull, and sawdust were 8, 15, and 15 dry tons per truck, respectively. These values were estimated from the average material quantities delivered to the pelletizing plant. The cost to deliver a ton of corn stover, seed hull, and sawdust using 8, 15, and 15 dry tons per truck were estimated at $0.02, $0.016, and $0.016 $ dry-ton^{-1} km^{-1}.

After being delivered to the pelletizing plant, items would arrive at the material storage and would be converted to material flow. Three materials were mixed in specific proportions and were sent to the processing machines. The plant is set to operate 24 hours, but one third of the total time is usually lost to repair, maintenance and emergency shutdowns. After pelletizing, products are stored at the product storage area ready to be shipped out. A pelletized material truck item, which deducts material from the product storage, was generated based on the actual record of shipped product.

Simulation was run for 77 days and the result of the simulation in terms of pelletized biomass output is shown in the **Figure 3.10.**

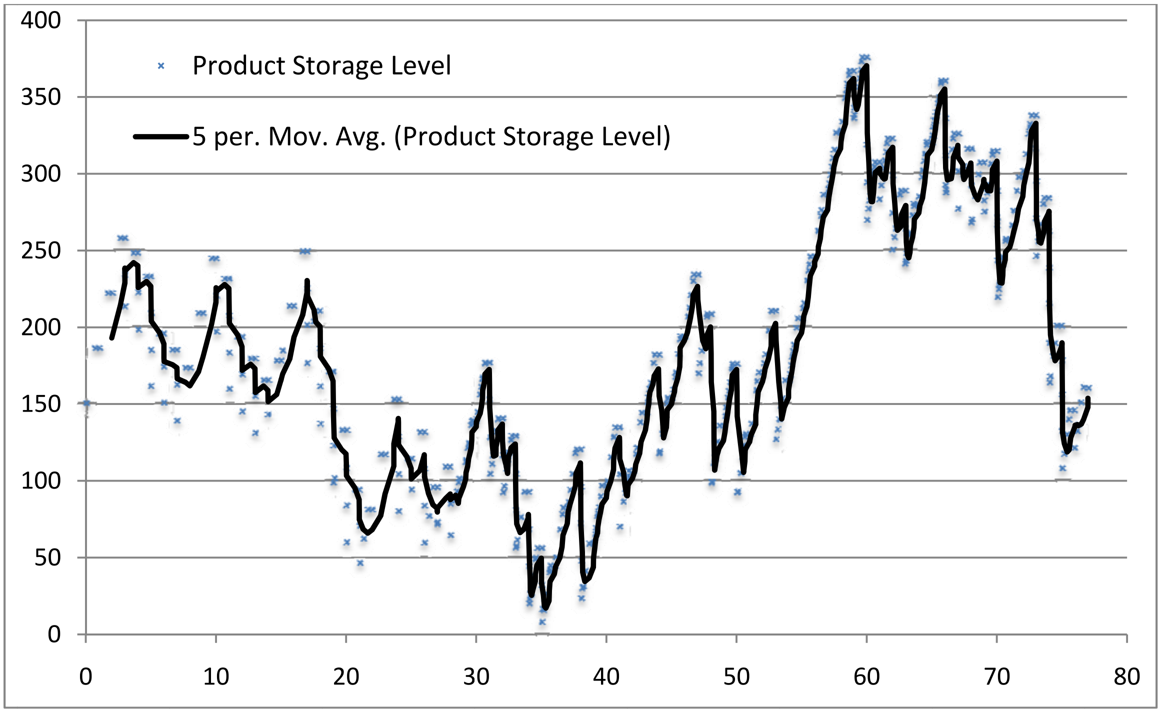

Figure 3.10 Product inventory level

The level of pelletized biomass inventory ranged between 2860 and 3225 tons, with a 375 dry ton difference between the minimum and maximum. The result of the inventory was consisted with the storage limits size of 400 dry tons.

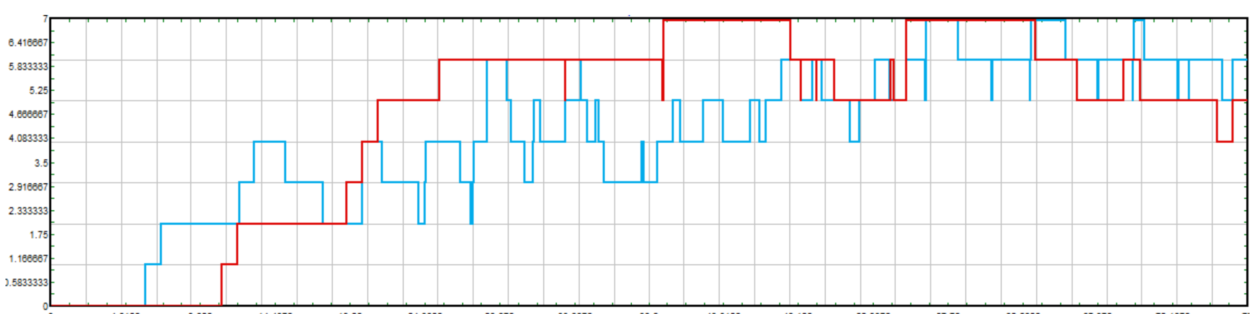

Figure 3.11 – Material inventory of seed hull (blue line) and sawdust (red line)

According to data from the pelletizing plant, the seed hull storage and sawdust storage can store up to 7 delivered trucks of material. The simulation result shows in **Figure 3.11** that the average amount of material was six trucks, and sometime reaches to seven trucks. Although there were some periods of time during which the number of trucks reached the maximum capacity of the storage, the storage might not have been full because of variations in the truck load.

Although, the plant was in a developing state and there was no detailed record of inventory to compare with the simulation results showed reasonable and consistent behavior of biomass material storage and pelletized biomass storage. Cost and energy results are shown in **Table 3.6**.

Table 3.9 Income and energy balance results in model verification

Simulation Results	
Pelletized biomass output (tons/day)	38.3
Net income ($/day)	1973
Net energy (MJ/day)	669244
Income per ton ($/ton)	51.5
Net Energy per ton (MJ/ton)	17492

According to data provided by the plant, the farmgate price of the material was at $5 ton^{-1} which is very low when compared to the estimated price of harvesting, and transporting operations by Kumar and Sokhansanj (2007). Income per unit could be lowered to approximately $33 ton^{-1} if the estimated cost from Kumar and Sokhansanj (2007) was used.

In summary, the biomass utilization system model was able to produce results consistent with the information given by the *Show Me Energy* Coop. Levels of three material storages and product storage, which represent material flow inside the plant, show consistent behavior within the given ranges of system constraints.

CHAPTER 4

SIMULATION RESULTS

4.1 Scenarios design and development

The logistic model is a developed simulation tool to analyze the economic viability and energy balance of the whole biomass utilization system. The model is capable of determining the net income and energy balance in the biomass utilization system when various management strategies are applied. Two sets of scenarios were developed to investigate possible options to improve the performance of *Show Me Energy*, a biomass pelletizing plant in Centerview, Missouri. The first scenario set was developed to observe system behaviors and system performance for different plant settings and policies. The second scenario set included simulations of different biomass pelletizing plant capacities on a yearly production basis. This second scenario set was developed to find the approximate optimal plant capacity for the current material selections.

4.1.1 Plant settings and policies

To observe the behaviors and performance of the biomass pelletizing system, six scenarios were simulated with four maximum transport distances: the shortest radius of transportation (SRT), 100 miles, 200 miles, and 300 miles. These four radial distances were used to test, for each scenario, how far away the plant could gather material from and still produce a profit, and a positive net energy output. The shortest radius of transportation (SRT) is the least radial distance required to supply enough material for the pelletizing plant to operate continuously (year-round). The other distances of 100 miles, 200 miles, and 300 miles were used as maximum possible distances of material transportation. These three maximum distances, which were larger than the shortest radius of transportation, should cover an area with enough material for the current pelletizing plant to operate year-round at the current capacity.

The biomass pelletizing plant is set to operate 24 hours per day, but 30% is for maintenance and emergency breakdowns. For handling and transportation operations, if the material delivery trucks are owned by the producers, trucks sizes could vary. Material price increases with the distance between the pelletizing plant and the material site. However, if the truck is operated by the pelletizing plant or a third-party logistics provider, it is assumed that semi trucks with a capacity of 22 tons will be chosen for biomass delivery. Cost and energy in transportation can be calculated from the data in **Tables 3.3** and **3.4**. With the semi truck method of transportation, the material price will be \$5 ton^{-1}, which is farmgate price as the agreed on by the biomass pelletizing plant and the material producer. Costs for delivery trucks and hiring truck drivers are incurred by the plant at \$70 hour^{-1} (Duffy, 2008), and \$15 hour^{-1}, respectively. It is assumed that each truck will be filled to its maximum capacity for each delivery run to maximize truck utilization. Because of differences in moisture content of corn stover, seed hull, and sawdust, the dry materials on the 22-ton truck are estimated at 18.7, 20, and 20 *dry tons*, respectively. Details of each scenario are described below:

Scenario 1: The actual plant setting with actual truck method of transportation – The pelletizing plant, which uses corn stover, seed hull, and sawdust as biomass material, has an average production rate at 2.4 dry tons hour^{-1}. Delivery truck sizes are varied because the trucks are operated by the material producers; hence the prices of materials are varied with the transport distance between the plant and the material production site. The average truck size for corn stover, seed hull, and sawdust delivery were estimated at 8, 15, and 15 dry tons, respectively. These were based on the delivery material record from the plant. The simulation was run for 77 days which was the period of time when the delivery material record was available.

For the simulation of shortest radius of transportation (SRT), the actual transportation distances from the plant record were used. It was assumed that the plant would get the closest available biomass material first to minimize material cost and then go farther transportation distances. In simulating the 100, 200, and 300 miles transportation distances, the price of the biomass was adjusted according to the actual price plan, given by the pelletizing plant.

Scenario 2: The actual plant setting with semi truck method of transportation – The pelletizing plant operates at the original production rate with corn stover, seed hull, and sawdust as biomass materials. Semi trucks with a capacity of 22 tons are used for material delivery. The simulation is run for 77 days, same as Scenario 1.

Scenario 3: Higher production rate with semi truck method of transportation – The pelletizing plant is operated at higher production rate of 6.76 dry tons $hour^{-1}$ as a result of major modification in the plant. Corn stover, seed hull, and sawdust are used as biomass materials. Semi trucks with a capacity of 22 tons are used for material delivery. The simulation is run for 60 days.

Scenario 4: Two production lines with semi truck method of transportation – The pelletizing plant is installed with another line to double the production rate to 13.52 dry tons $hour^{-1}$. Corn stover, seed hull, and sawdust are used as biomass materials. Semi trucks with a capacity of 22 tons are used for material delivery. The simulation is run for 60 days.

Scenario 5: Two production lines using switchgrass with semi truck method of transportation – The pelletizing plant with double production rate (13.52 dry tons hour^{-1}) use switchgrass, seed hull, and sawdust as biomass materials. Switchgrass, a hay-type biomass, is used instead of corn stover. Semi trucks capacity of 22 tons are used for material delivery. The simulation is run for 60 days.

Scenario 6: Two production lines using miscanthus with semi truck method of transportation – The pelletizing plant with double production rate (13.52 dry tons hour^{-1}) use miscanthus, seed hull, and sawdust as biomass materials. Miscanthus, a hay-type biomass, is used instead of corn stover. Semi trucks of 22-tons are used for material delivery. The simulation is run for 60 days.

4.1.2 Plant capacity for year-round operation

Nine scenarios were developed to observe system performance of different plant capacities when the plant is operated year-round. Material is produced and delivered from the least radial distance required to provide sufficient material for the biomass pelletizing plant to operate 360 days a year. The area used for material production and the material transportation distance are varied by the plant capacity. It is assumed that 75 % of the land is used by crop production and

75 % of the crops or residue can be used as biomass material. The pelletizing plant is operated 24 hours a day, but 30% of operating time is lost to maintenance and emergency shutdowns.

Semi trucks with a capacity of 22 tons are used as transporters, and are operated by a third-party logistics provider. To maximize truck utilization, it is assumed that each truck will be filled to its maximum capacity. Because of differences in moisture content, the dry ton capacities of the 22-ton truck are estimated at 18.7, 20, and 20 for corn stover, seed hull, and sawdust, respectively. Material will be sold to the pelletizing plant at \$5 ton^{-1} which is the farmgate price. The truck operation costs are \$70 hour^{-1} and \$15 hour^{-1} for truck rental and hiring a driver, respectively (Duffy, 2008).

The current plant capacity, a single pelletizing line with a throughput of 6.76 tons hour^{-1}, was simulated as the first scenario. Scenarios 2 to 8 are simulation of 5, 10, 15, 20, 25, 30, 35, and 40 pelletizing machine lines. The plant, which required a total of 7 workers, was assumed to require two more workers for each extra line. Input energy for the plant was increased by the number the production lines installed; however the capital cost of each extra pelletizing line was estimated at 70 % of the current production line due to sharing in capital costs of land and machines. Detailed of costs and energy usage are shown in **Tables 3.6** and **3.7.**

4.2 Results and discussion

4.2.1 Plant settings and policies

Simulation results of the six scenarios with four transportation distances are recorded and shown in **Tables 4.1** and **4.2**.

Table 4.1 – Profit (\$ dry ton^{-1}) of pelletized biomass product

Scenario	SRT	100 miles	200 miles	300 miles
1. Actual plant setting and truck	-20.8	-26.6	-36.1	-49.2
2. Actual plant setting and semi truck	-14.9	-16.5	-32.8	-41.7
3. Higher production rate and semi truck	56.8	48.7	38.3	28.7
4. Double production line and semi truck	65.4	56.7	45.9	35.6
5. Double production line using swtichgrass and semi truck	29.8	19.1	8.4	-2.5
6. Double production line using miscanthus and semi truck	50.1	38.4	29.8	19.0

The net profit for each scenario in **Table 4.1** results from subtracting the investment costs (which include cultivation, transportation, pelletization, repair and maintenance, and capital investment costs) from the income from selling pelletized biomass. In scenario 4, 5, and 6, the cost for installing an extra pelletizing linewas approximated at 70% of the cost to build the plant.

The net energy (MJ dry ton^{-1}) in **Table 4.2** are the net energy content of pelletized biomass after subtracting the energy used in material production, handling and transportation pelletization.

Table 4.2 – Net energy balance (MJ dry ton^{-1}) of pelletized biomass product

Scenario	SRT	100 miles	200 miles	300 miles
1. Actual plant setting and truck	17,491	17,334	17,056	16,781
2. Actual plant setting and semi truck	17,611	17,589	17,338	17,201
3. Higher production rate and semi truck	17,744	17,589	17,430	17,262
4. Double production line and semi truck	17,795	17,632	17,465	17,291
5. Double production line using swtichgrass and semi truck	17,141	16,977	16,810	16,643
6. Double production line using miscanthus and semi truck	17,457	17,260	17,126	16,959

4.2.1.1 Truck method of transportation

Scenarios 1 and 2 were simulated to show the differences in average cost and energy if the pelletizing plant switched to operating trucks by itself. There was no difference in the settings for material production or the biomass pelletizing plant, and thus the comparison was specific about the transportation part of the system. In either scenario, the operation would result in a negative profit (loss) if equipment depreciation cost were included. From **Table 4.1**, Scenario 2, which uses the semi truck size, shows a better average profit per ton, though still a loss if production cost is included. In Scenario 2, by switching to the larger truck size, the plant will take responsibility for the truck operation cost, which includes rental cost, driver cost, and fuel cost. However, the plant also gains because the material cost drops to farmgate price at \$5 ton^{-1} based on information from the pelletizing plant. Comparison of energy usage in transportation is presented in **Table 4.3**.

Table 4.3 – Energy consumption (MJ) in transportation

Scenario	SRT	100 miles	200 miles	300 miles
Actual plant setting and truck	679,444	1,143,177	1,962,049	2,770,775
Actual plant setting and semi truck	324,886	390,034	1,130,634	1,534,985

Results show that energy usage in transportation for Scenario 2 is lower than that for Scenario 1 by an average of 54%. Scenario 1, which uses smaller trucks, consumes more energy in transportation because of the higher energy consumption rate per dry ton. The results and trend of net income and net energy balance are showed in **Figures 4.1** and **4.2**.

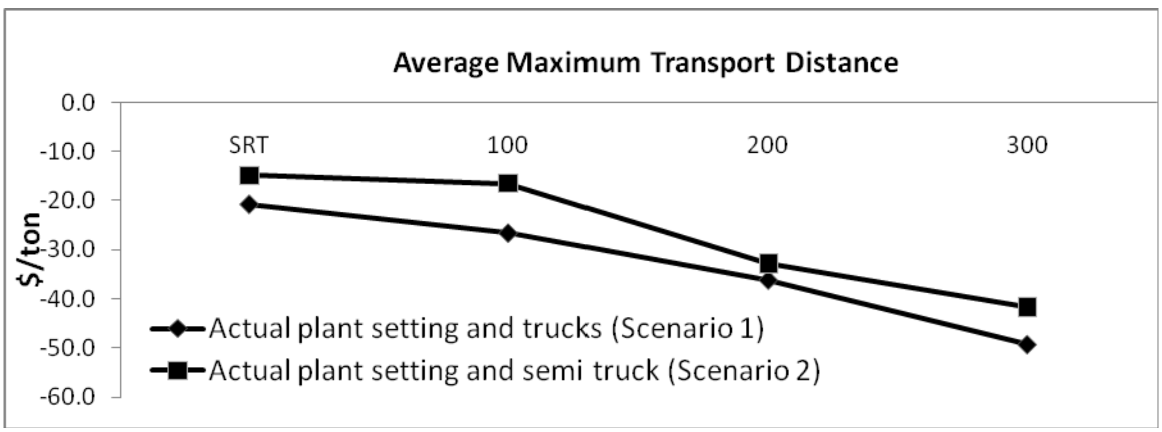

Figure 4.1 – Net income of pelletized biomass ($ dry ton^{-1}) in Scenario1 vs. Scenario2

From **Figure 4.1**, Scenario 2 provides better net income ranging from $2 to $9 ton^{-1}, compared to Scenario 1. The difference in net income tends to increase with longer maximum transport distance. Net energy balance also shows an increasing in gap between the two scenarios. Using semi trucks could increase net energy balance from 0.7% to 2. 5%, compared to Scenario 1.

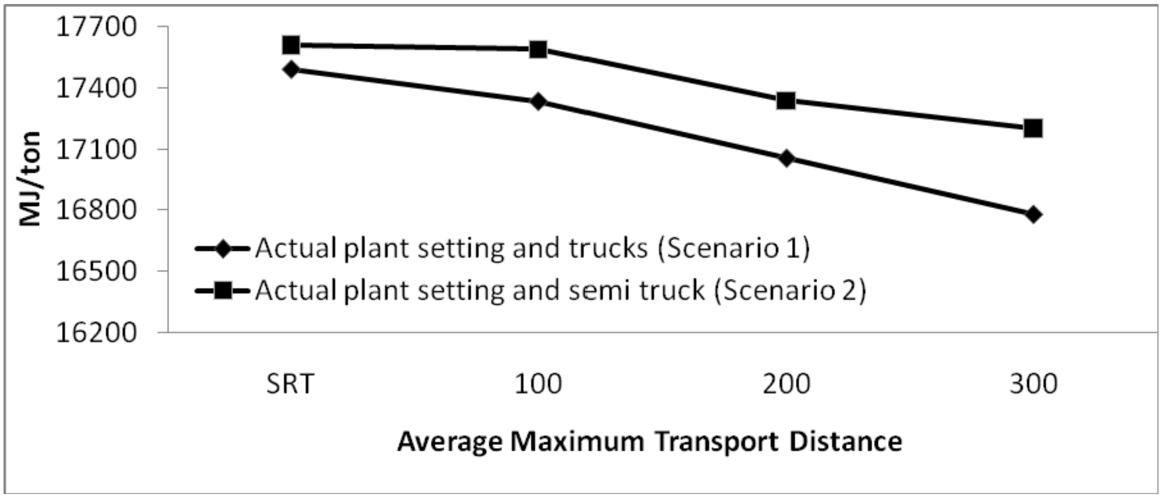

Figure 4.2 – Net energy balance of pelletized biomass (MJ dry ton^{-1}) in Scenario1 vs. Scenario2

Because of the low throughput at an average of 2.4 dry tons hour^{-1}, both scenarios could not make enough profit to cover the capital cost, which is estimated at \$2600 day^{-1} over a 15-year lifetime. These two scenarios provide insight that transportation with a larger truck provides better performance in term of net income and net energy output. Particularly, energy usage in transportation is decreased by an average 54% by switching to semi trucks of 22 tons.

4.2.1.2 Pelletizing plant capacity

Scenarios 3 and 4 were simulated to see the differences in system performance when increasing the average transportation distance and the plant capacity by installing another pelletizing line in Scenario 4. Scenario 3, which uses a new production rate as a result of plant modification, can also be used to compare with Scenario 2 which has a lower production rate but similar input cost and energy. The modification was done to reduce material flow obstacles in the plant.

Comparing results between Scenario 2 and Scenario 3 in **Table 4.1** shows that increasing throughput of a single pelletizing line from 2.4 dry tons hour^{-1} to 6.76 dry tons hour^{-1} helps the pelletizing plant to absorb the extra capital cost and stay viable positive profit; Scenario 3 could increase the net income by an average \$69.6 dry ton^{-1}.

In Scenario 4, another line was installed to the plant. The cost of utilities double, and the plant needed 2 additional workers for operating another production line. Therefore, Scenario 3 required total of 5 workers while Scenario 4 required 7 workers. The graph of net income and net energy balance are shown in **Figures 4.3** and **4.4**.

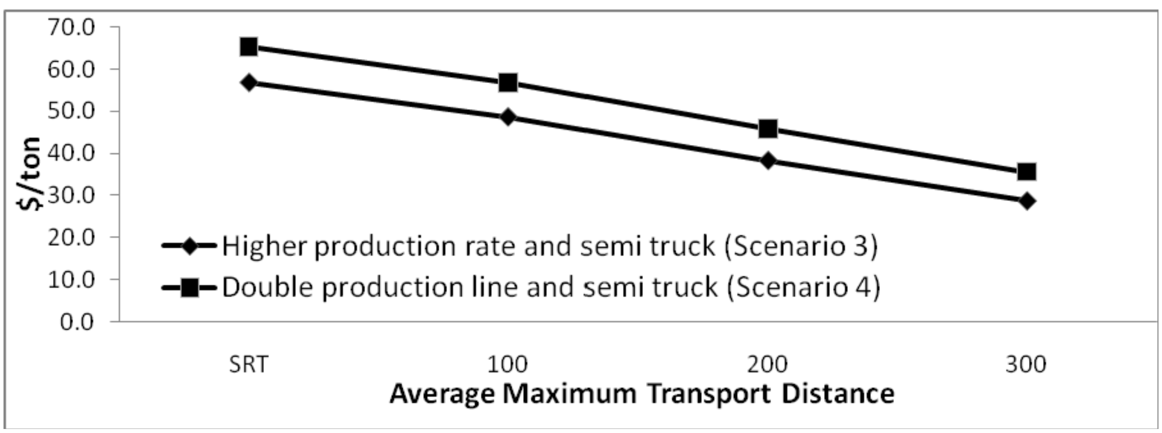

Figure 4.3 – Net income of pelletized biomass (\$ dry ton^{-1}) in Scenario 3 vs. Scenario 4

In Scenario 4, installing another production line increases net income by an average of \$7.7 dry ton^{-1}. This is the result of land and worker sharing which help to reduce capital cost and increase the net profit. There is a small decrease in net energy when increasing the plant capacity because of increased radius of transportation for gathering additional material. As expected, increasing the transport distance will result in reduction of net income and net energy in both scenarios.

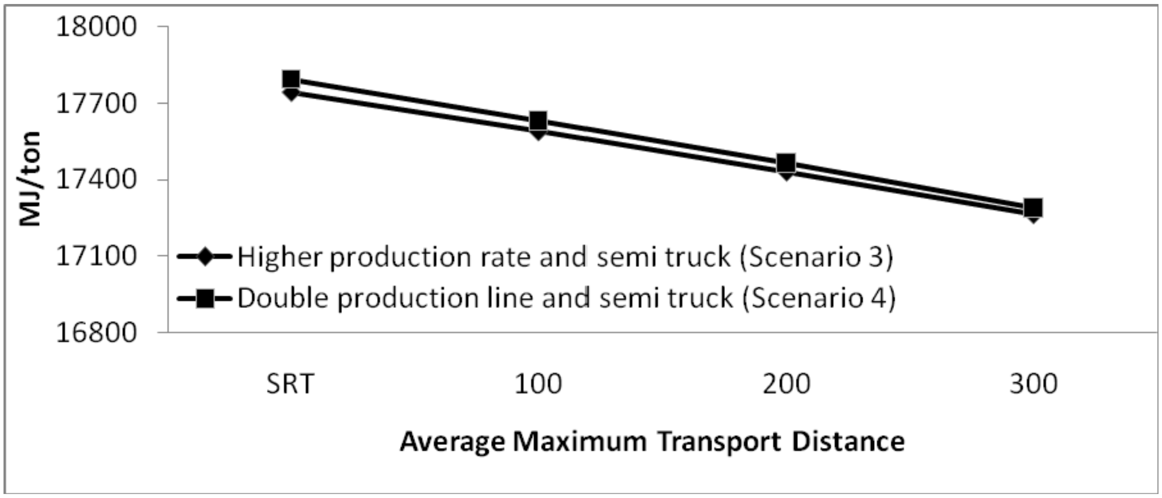

Figure 4.4 – Net energy balance of pelletized biomass (MJ dry ton^{-1}) in Scenario3 vs. Scenario4

These two scenarios show the importance of increasing the plant capacity. Increasing the throughput drastically increases net income per dry ton and improves the viability of the plant compared to Scenario 2, which has a negative net income after including the crop production and capital costs.

4.2.1.3 Material selection

The results of Scenarios 4, 5, and 6 are compared for biomass selection maximizes profitability of the biomass pelletizing plant. Switchgrass and miscanthus, two high potential biomass crops, are selected to compare with the corn stover that is currently used in the pelletizing plant.

Corn stover, a residue from corn cultivation, has the main advantages of low cost and energy input for material production. On the other hand, switchgrass and miscanthus have the advantage of greater yield compared to corn stover. A pelletizing plant with double capacity, which is supplied with corn stover, seed hull, and sawdust, was simulated in Scenario 4. Corn stover was substituted by switchgrass and miscanthus in Scenarios 5 and 6, respectively. There was no change in transportation and the pelletizing plant, except the shortest radius of transportation which was varied with the yield of the selected biomass material. Data of cost and input energy for cultivation of switchgrass and miscanthus were collected from a local producer in Missouri and are shown in **Table 3.2**. The simulation results of net income and net energy balance are shown in **Figures 4.5** and **4.6**.

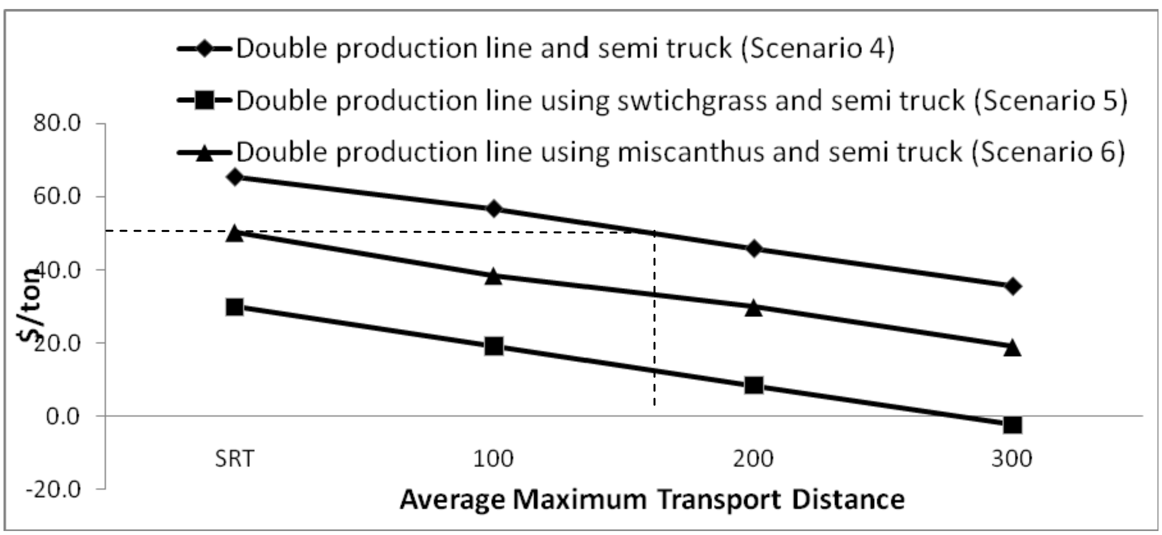

Figure 4.5 – Net income of pelletized biomass ($ dry ton^{-1}) in Scenario 4, Scenario 5, and Scenario 6

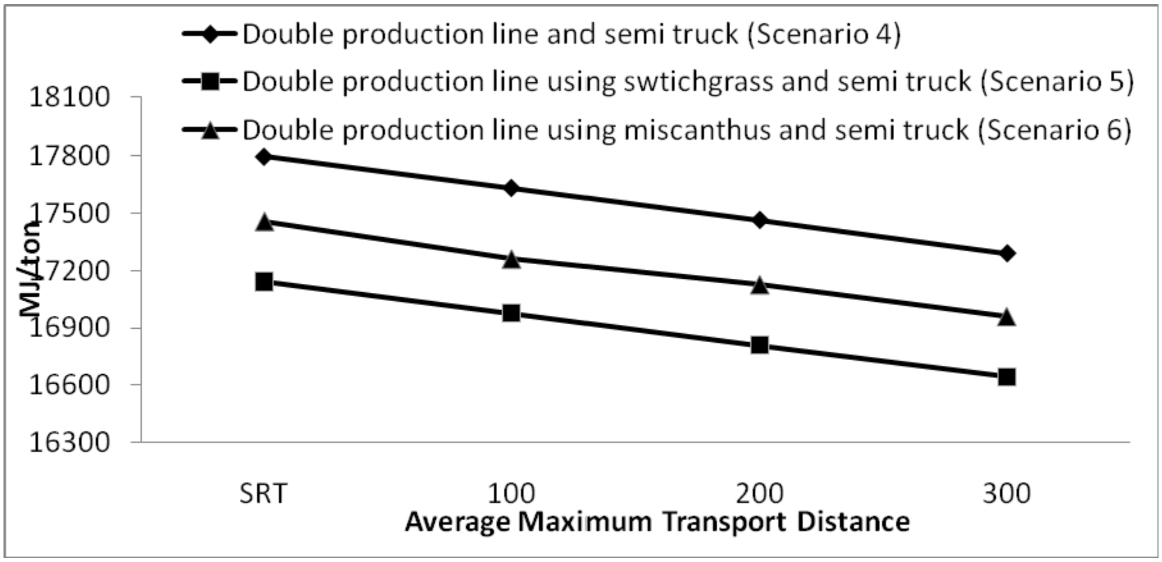

Figure 4.6 – Net energy balance of pelletized biomass (MJ dry ton^{-1}) in Scenario 4, Scenario 5, and Scenario 6

Using corn stover, which is a residue from corn production, provides the most economic benefit to the biomass pelletizing plant. Between the two cultivated biomass crops, miscanthus has better performance because of the higher yield and lower cost and energy inputs. Corn stover provides better net income than switchgrass and miscanthus by an average of $37.2 and $16.5 dry ton^{-1}, respectively. For net energy balance, corn stover also provides a better output than switchgrass and miscanthus by an average of 653 and 345 MJ dry ton^{-1}.

Although the yields of switchgrass and miscanthus are approximately three to five times that of corn stover, the benefit from shorter transport distance is still not significant enough to compensate for the extra cost and energy used in the cultivation of the biomass crops.

Results from **Figure 4.5** also suggest that corn stover could be switched to Miscanthus to increase profit, if the plant needs to go further than 170 miles. Based on results from **Figure 4.6**, miscanthus will start to provide better net energy balance when corn stover needs to be picked up from farther than 230 miles. Therefore, it is suggested to switch from corn stover to miscanthus between 150 and 230 miles of transportation.

4.2.2 Plant capacity for year-round basis operation

Nine scenarios of the biomass pelletizing plant were simulated for a year of production to study the system performance when the plant capacity was increased. By increasing the plant capacity, the system benefits from reduction of the average capital cost because of sharing of land, machines, and tools inside the facility. However increasing plant capacity also requires more area for material production, and thus increasing the average transport distance. This will result in increased cost and energy used for transportation. Therefore, the increase in net income ($ ton^{-1}) is gradually decreased as the plant grows larger. As shown in **Figure 4.7**, the net income reaches its maximum at a total of 25 lines and starts to drop if more pelletizing machines are installed.

In contrast to the net income, the net energy balance of pelletized biomass could not get any benefit from increasing the plant capacity. Increasing the average transport distance results in higher energy consumption in the transportation and lower net energy balance. As the results shown in **Figure 4.8** indicate, the net energy gradually decrease at a decreasing rate, which is the result of slower transport distance increase for larger areas. However, this reduction of the net energy balance could be considered as an insignificant factor because of the relatively small amount of energy lost (lower than 0.003% of total net energy.)

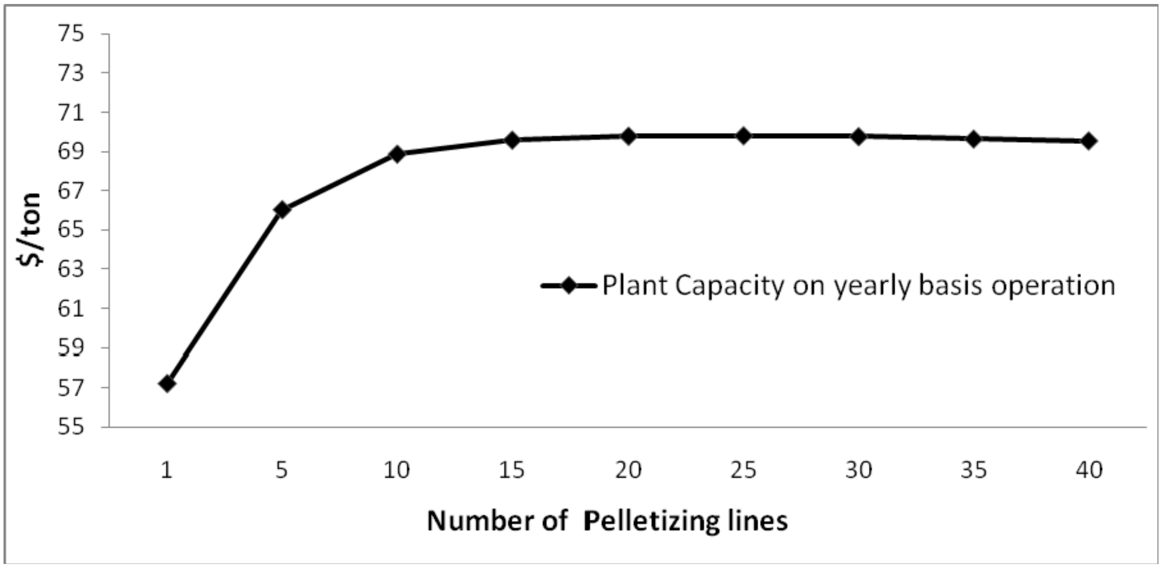

Figure 4.7 – Net income of pelletized biomass ($ dry ton^{-1}) when increasing pelletizing lines

The maximum net income per ton is between 25 and 20 pelletizing lines. In terms of both cost effectiveness and energy effectiveness, 5 to 10 times the current plant capacity provides the highest performance, because there is relatively small increase in net income between 10 to 25 pelletizing machine lines but additional energy lost to transportation.

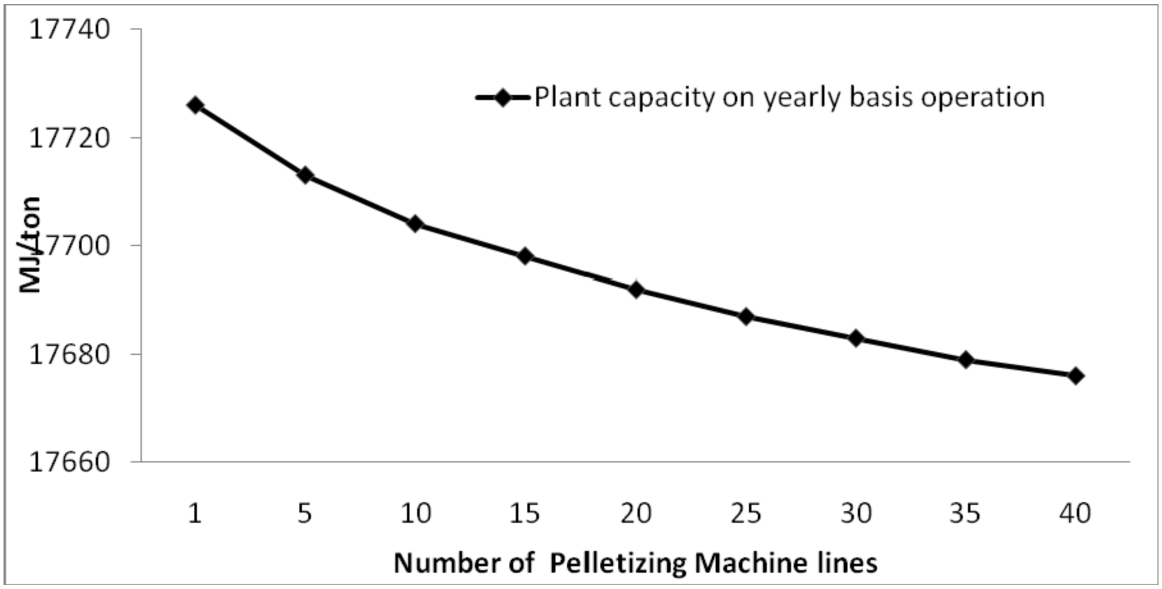

Figure 4.8 – Net energy balance of pelletized biomass (MJ dry ton^{-1}) when increasing pelletizing lines

For the net energy balance, the simulations show contrast results to the intuitive belief that larger plant capacity could always lead to a higher cost of transportation and thus lower profit. Transport distance and cost for energy in transportation increased at a lower rate compared to saving from increasing the plant capacity under a certain capacity value.

CHAPTER 5

CONCLUSION

5.1 Summary

A logistic model of a biomass utilization system was developed in ExtendSim, a simulation program, to help analyze the complex-behavior of the biomass supply chain. The model is capable of describing the characteristics of Show Me Energy Coop, a pelletizing plant in Centerview, MO. It was developed to a decision-making tool to analyze the economic availability and net energy balance of the biomass pelletizing system. Different scenarios were simulated to observe the cause and effect in transportation, plant capacity, and material selection.

Simulation results suggest that the current truck policy, which uses varied truck sizes, could be changed to semi trucks of 22-ton capacity, to improve transportation performance. Increasing the truck size to semi trucks could reduce energy use in transportation by approximately 54 %.

Increasing plant capacity helps reduce the capital cost per unit product produced, hence increasing profitability. However, this also results in increased land size for biomass material production and transport distance. Therefore, larger plant capacity will result in increasing net income at a decreasing rate.

Corn stover, which is currently used as a biomass material, was compared with switchgrass and miscanthus to observe differences in system performance. Although, switchgrass and miscanthus could provide higher material yield, which is normally used as a key factor for selecting biomass crops, corn stover, a residue from grain production, results in better net income and net energy balance. Simulation results suggest that biomass residue, which does not require input for material production, results in a better solution in comparison to biomass crops. If the corn stover needs to be transported farther than 170 miles, it is more profitable to switch material from corn stover to miscanthus if available around the plant location. However, the net energy output of miscanthus will be lower than that from corn stover until corn stover needs to be picked up farther than 230 miles. Therefore, the plant may switch material from corn stover to miscanthus if corn stover is transported from a location farther than 170 miles away.

Increasing the plant production throughput affects the plant profitability the most. This can be observed from the increases in net income and net energy after the plant modification to improve material flow. This shows the importance of research and development for a more efficient pelletization process.

Increasing plant capacity by installing extra pelletizing lines increases net income of the system by sharing of capital cost, but at the same time, net energy balance is decreased because of increasing transport distance for gathering more material. However, the reduction net energy is not large compared to the total net energy balance; therefore it is recommended to build the plant up to 10 pelletizing lines.

In summary, logistic modeling for biomass utilization allows estimation of net income and net energy from a system. The simulation model for this multi-biomass system can be used as a decision-making tool to observe system performance when different settings or policies are applied.

5.2 Recommendations for further research

With the complexity of supply chain systems, there are many future research opportunities for biomass utilization systems. In material production, there are other high-potential biomass crops that should be compared with corn stover. Performances in harvesting, handling, and transportation are depending mainly on machine performance. Machine selection and possible machine modification for handling biomass are interesting issues that need to be analyzed for optimization. Last but not least, there is still a need for research in the pelletization operation. To handle different mix of biomass materials, the pelletizing plant should be simulated to find the most suitable configuration wide range of material conditions.

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