A Computer-aided Model to Operations System to Optimize Woody Biomass Feedstock Storage and Transportation

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Due to the greater demand in bioenergy and bio-based products, feedstock supply chain optimization is critical to decrease the logistics costs. As a primary phase in the biomass feedstock supply logistics, the storage of harvested biomass can directly affect transportation cost, biomass quality and its combustion efficiency. A model structured with linear programming was developed to determine an optimized biomass pre-processing, storage, and transportation strategy. The optimization model was applied in a simulated case study for an energy plant in Michigan. The results indicated that lower supply chain logistics costs and higher feedstock quality could be achieved by applying an optimized supply chain strategy while simultaneously meeting the feedstock user’s demand. The sensitivity analysis indicated that transportation distance had no impact on the supply chain logistics strategy. The additional profit brought by higher quality biomass can offset the increased transportation cost for up to 151 miles. Through biomass MC increases, logging residue pile is always the preferred storage method. The impact of biomass moisture content (MC) is concluded to be more significant when it is higher. Through the increase of biomass MC, more biomass is required to satisfy the same energy demand. In average, every 1% increase in biomass MC can result in $760.68 increase in total cost and 52.1 more green tons biomass to satisfy the four-month energy demands.

1. Introduction

As a carbon neutral and renewable fuel, forest-based biomass has gained popularity in recent years and has been commonly used by independent power plants to generate energy in U.S (Biomass Energy Resource Center, 2011). 541 Exajoules (EJ) energy was consumed in the world during 2010, and about 9% of the energy consumption was generated from woody
biomass (IEA, 2013; Lauri et al., 2014). Due to the ever-increasing demand of bioenergy, the number of biomass power plants will be steadily increasing (Berndes et al., 2003; Jager-Waldau and Ossenbrink, 2004). The increasing number of power plants will bring more restrictions and higher complexity for the management of the woody biomass supply chain (Rönnqvist, 2003). In addition, the relatively scattered locations of the power plants will largely increase the transportation distances and costs for forest biomass (Rauch and Gronalt, 2010; Tahvanainen and Perttu, 2011; Alam et al., 2012). Therefore, supply chain optimization for biomass-based power plants is becoming an important research area (Tallaksen and Simo-Kush, 2014).

With the development of computational tools, mathematical models for optimization were widely used to implement cost-effective biofuel production (Macmillan, 2001; Mentzer, 2001; Rönnqvist, 2003; Gunnarsson et al., 2004; Bredström, 2004). As biomass transportation cost accounts for the largest part of the total cost, the developed optimization tools primarily focus on two categories: location selection and biomass transportation cost reduction (Eriksson and Bjo¨rheden, 1989; Allen et al., 1998; Alam et al., 2012). The location selection models mainly focused on finding the best location for single or multiple processing facilities over large-scale biomass-supply chain (Zhang et al., 2011). The transportation cost reduction models generally aimed to reduce cost for biomass procurement and to estimate the feedstock availability (Ranta, 2002; Ranta, 2005; Panichelli and Gnansounou, 2008). However, as a critical phase in woody biomass supply chain logistics, woody biomass storage was rarely studied (Rentizelas et al., 2009).

Storage is important because of the changing seasonal availability of woody biomass and the varied demand of energy plants throughout the year (Sokhansanj et al., 2006; Lin and Pan, 2013). Meanwhile, different storage methods will produce biomass at various quality levels, which can significantly affect the transportation cost and combustion efficiency (Jirjis, 2005; Casal et al., 2012). The most common way in Northern U.S. to store green biomass is to directly process it into wood chips and store in piles before being utilization (Lin and Pan, 2013). This storage method poses several challenges such as dry matter loss, moisture content increase, and energy content reduction (Fredholm and Jirjis, 1988; Hornqvist and Jirjis, 1999; Jirjis 2001; FRL, 2002; Afzal et al, 2010). Store forest harvesting residue in bundles can produce high quality biomass feedstock with low biomass MC, higher energy content and low ash content (Lehtikangas, 2001; Pettersson and Nordfjell, 2007; Afzal et al., 2010). Yet, the bundling technology is also associated with several problems such as high capital investment and low productivity caused by saw binding, materials handling, twine spool collapse, and slow movement at the harvesting site (Rummer et al. 2004; Leinonen, 2004; Patterson et al., 2008; Harrill, 2010). Compared to wood chips pile and biomass bundles, storing unprocessed...
harvesting residue can achieve lower processing cost and effectively reduce biomass MC, thus increasing transportation and conversion efficiency (W.A. Amos, 1998; Lin and Pan, 2013; Lin and Pan, 2015).

Michigan is a state with 84% forest cover, forest resources have been viewed as a widely available and promising resource for energy production in Michigan (Dickmann and Leefers, 2003; Zhang et al., 2011). In Michigan, there are 9 biomass-based power plants with a total amount of 210 MW energy generated annually (Biomass Power Association, 2014). Due to weather, ground conditions, or biological constraints, forest harvesting operations are not always possible. To ensure a cost-effective, year-round reliable supply of high quality biomass feedstock to the power plants, a computer-aided optimized operations system was developed. The objectives of this paper are: 1) to develop an optimized operations system that can increase biomass feedstock quality and minimize the storage and transportation costs; 2) to test the effect of transportation distance and biomass MC on supply chain logistics strategy and the total cost.

2. Problem description

Feedstock storage and transportation operations

Since the prediction of biomass MC during storage is based on two previous studies conducted from August to November, the woody biomass is assumed to be harvested at the end of July and be stored from August to November. The selected harvesting site is a natural forest stand with a mixture of hardwood and softwood species, 40 miles away from the feedstock end-user: the Cadillac Renewable Energy. Part of the harvested woody biomass is going to be in-woods chipped, transported to and stored in the Cadillac Renewable Energy to meet its first month demand. The rest of woody biomass is to be stored at the harvesting site as unprocessed residue piles for a certain time and then be chipped and be transported to the Cadillac Renewable Energy based on its continued demand.

Feedstock end-user

The Cadillac Renewable Energy, located in Cadillac, Michigan, has a 38MW energy production capability. It is exclusively designed to use recycled wood waste as its primary fuel source. Average monthly use of woody material (in approximately 45% MC) is about 35,000 green tons in wintertime and around 25,000 tons in other months. There are about 40 logging
companies constantly supplying woody biomass to Cadillac Renewable Energy. Therefore, it is assumed that each supplier needs to deliver 550 dry tons of woody biomass in every month.

**Traditional operation system and optimized operation system**

In this study, the traditional operation system refers to the traditional way of handling harvested biomass, where harvested logging residue is directly processed into wood chips and immediately delivered to the feedstock user, then stored in wood chips pile (WCP). In the optimized operation system, one portion of the harvested biomass will be processed right away and delivered to feedstock user, while the rest unprocessed portion is to be stored in the form of logging residues pile (LRP) at the harvesting site. After a certain time of in-woods drying, unprocessed logging residues will be chipped by a mobile chipper and delivered to feedstock end-user.

![Diagram of biomass supply chain](image)

**Figure 1.** An illustration of the optimized woody biomass supply chain system includes biomass processing, storage and transportation.

**Biomass storage**

In the optimized operations system, storage and transportation cost is closely related to the woody biomass MC, which is significantly affected by the storage form. The monthly MC of a wood chips pile is based on the previous study conducted in Michigan from August to November 2013 (Lin and Pan, 2015, Table 1). The monthly MC of logging residue pile is predicted using the formula developed in a previous study and the local weather conditions from August to November 2013 (Lin and Pan, 2013).
Table 1. Monthly Biomass MC (Lin and Pan, 2013; Lin and Pan, 2015)

<table>
<thead>
<tr>
<th>Biomass MC (%)</th>
<th>Wood Chips Pile (WCP)</th>
<th>Logging Residues Pile (LCP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>40.3%</td>
<td>23.8%</td>
</tr>
<tr>
<td>September</td>
<td>39.3%</td>
<td>18.1%</td>
</tr>
<tr>
<td>October</td>
<td>40.7%</td>
<td>26.1%</td>
</tr>
<tr>
<td>November</td>
<td>45.5%</td>
<td>25.9%</td>
</tr>
</tbody>
</table>

**Transportation costs**

The transportation distance is set to be 40 miles in the case study. The transportation cost in dollars per green ton is estimated based on the equation that was developed for Lower Peninsula, Michigan (Lautala et al., 2012). The transportation costs associated with different distances are provided in Table 2.

Table 2. Transportation costs with different transportation distances

<table>
<thead>
<tr>
<th>Transportation distance (miles)</th>
<th>Transportation cost ($/green ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>5.88</td>
</tr>
<tr>
<td>30</td>
<td>6.42</td>
</tr>
<tr>
<td>40</td>
<td>6.97</td>
</tr>
<tr>
<td>50</td>
<td>7.52</td>
</tr>
<tr>
<td>60</td>
<td>8.07</td>
</tr>
</tbody>
</table>

**Holding cost (HC) and additional profit (AP)**

In the optimized operation system, part of the fresh harvested biomass is going to be stored as logging residues piles at the harvesting site for air-drying. This will delay the loggers’ cash flow and lead to future costs such as machine mobilization and transportation cost. However, it is beneficial for feedstock end-user to use drier wood fuels with higher energy content and lower MC, to increase boiler combustion efficiency. To offer a motivation and
profit for loggers to store biomass in logging residue pile, it is assumed that purchasing price for woody biomass is based on their net energy content, which largely depends on biomass MC. Therefore, drier biomass has higher purchasing price. The standard purchasing price for wood chips is $23/green ton for woody biomass at around 45% MC (Larry Heibel, personal contact, June 11th, 2014; Nate Verhanovitz, personal contact, June 25th, 2014). The net energy content of the wood (NEC) can be estimated using the equation below:

\[ NEC = HHV \times (1 - MC/100) \] (Maker, 2004).

Where:

HHV is the higher heating value of the oven dry biomass,

MC is the moisture content of the received biomass.

If the HHV of the woody biomass is assumed to be 8400 BTUs/lb., the NET of 45% MC woody biomass is 4620.00 BTUs/lb. based on the above equation. Therefore, the energy cost in dollar per BTUs can be calculated by dividing standard purchasing price by the net energy content in the wood chips. For biomass with different MC, the purchasing prices are calculated and listed in Table 3.

### Table 3. Calculated prices for wood chips based on NEC

<table>
<thead>
<tr>
<th>Biomass MC (%)</th>
<th>HHV (BTUs/lb)</th>
<th>NEC (BTUs/lb)</th>
<th>Purchasing price ($/green ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60%</td>
<td>8400</td>
<td>3360.00</td>
<td>16.73</td>
</tr>
<tr>
<td>55%</td>
<td>8400</td>
<td>3780.00</td>
<td>18.82</td>
</tr>
<tr>
<td>50%</td>
<td>8400</td>
<td>4200.00</td>
<td>20.91</td>
</tr>
<tr>
<td>45%</td>
<td>8400</td>
<td>4620.00</td>
<td>23.00</td>
</tr>
<tr>
<td>40%</td>
<td>8400</td>
<td>5040.00</td>
<td>25.09</td>
</tr>
</tbody>
</table>
3. Mathematical model

Indices

n: The storage length of the biomass (n=0, 1, 2, 3 months)

Variables

WC<sub>n</sub>: Weight of biomass harvested in July, stored in wood chips piles (WCP) for n months
WR<sub>n</sub>: Weight of biomass harvested in July, stored in logging residue piles (LRP) for n months

Figure 2. Monthly biomass weight delivered to the feedstock end-user
**Parameters**

DB: The monthly biomass demand in green tons (45% MC in wet-basis) for the energy plant

Z: The total cost of processing, storing and delivering the woody biomass

KC: The total chipping cost ($) for processing all the biomass

KP: The total piling cost ($) for shaping the logging residues into biomass piles

KMG: The machine mobilization cost ($) of moving the mobile grinder to the harvesting site

KML: The machine mobilization cost ($) of moving the loader to the harvesting site

KT: The transportation cost ($) of delivering chipped products to the feedstock end-user

AP: The additional profit earned by selling drier biomass

MC<sub>Cn</sub>: The MC of biomass harvested in July and stored in wood chips form for n month(s)

MC<sub>Rn</sub>: The MC of biomass harvested in July and stored in logging residues form for n month(s)

HHV: Higher heating value of the woody biomass (BTUs/lb.)

NEC<sub>Cn</sub>: Net energy content of wood chips (BTUs/lb.)

NEC<sub>Rn</sub>: Net energy content of logging residues (BTUs/lb.)

PC<sub>n</sub>: The purchasing price ($/green ton) of wood chips that were harvested in July and store for n month(s).

PR<sub>n</sub>: The purchasing price ($/green ton) of logging residues that were harvested in July and store for n month(s).

P<sub>s</sub>: The standard purchasing price (23 $/green ton) for energy plant to purchase biomass (45% wet-basis).

EC<sub>s</sub>: The purchasing price for 1 BTU of energy ($/BTUs).

HC: The costs ($) occur while holding the biomass store in logging residues piles.

**Constraints**

Satisfy the monthly demand of the energy plant

\[ [(1 - MC_{Cn}) \cdot WC_n + (1 - MC_{Rn}) \cdot WR_n] - (1 - 45\%) DB \geq 0 \]

where n = 0, 1, 2, 3 months.
Objective function

The total cost can be expressed as

\[ z = KC + KP + KMG + KML + KT - AP + HC \]

where \( AP = \sum_{n=0}^{3} (PC_n \cdot WC_n + PR_n \cdot WR_n) - PC_0 \cdot \sum_{n=0}^{3} (WC_n + WR_n) \)

\[ PC_n = \frac{2000 \text{ lbs}}{\text{green ton}} \cdot EC_s \cdot NEC_{cn} \]
\[ NEC_{cn} = \sum_{n=0}^{3} HHV (1 - MC_{cn}) \]

\[ PR_n = \frac{2000 \text{ lbs}}{\text{green ton}} \cdot EC_s \cdot NEC_{rn} \]
\[ NEC_{rn} = \sum_{n=0}^{3} HHV (1 - MC_{rn}) \]

\[ HC = WR_n \cdot PR_1 \cdot r \cdot t \cdot [1 + WR_n \cdot PR_1 (1 + r \cdot t) + WR_n \cdot PR_1 (1 + r \cdot t)^2 + WR_n \cdot PR_1 (1 + r \cdot t)^3] \cdot \]

n=0, 1, 2, 3 months; r=0.03 (yearly interest rate); t=1 month \( \approx 0.08 \) year.

Other values of the parameters are listed in Table 4.
### Table 4. Values of the parameters

<table>
<thead>
<tr>
<th>Site conditions</th>
<th>Cadillac Renewable Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock user</td>
<td>Cadillac Renewable Energy</td>
</tr>
<tr>
<td>Transportation distance (miles)</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Wood Chips Pile (WCP)</th>
<th>Logging Residues Pile (LCP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chipping cost ($/green ton)</td>
<td>5.00(1)</td>
<td>5.00(1)</td>
</tr>
<tr>
<td>Piling cost ($/green ton) (4)</td>
<td>0</td>
<td>4.59(2)</td>
</tr>
<tr>
<td>Machine mobilization cost ($/green ton) (5)</td>
<td>2.52(3)</td>
<td>2.52(3)</td>
</tr>
<tr>
<td>Total Processing cost ($/green ton)</td>
<td>7.52</td>
<td>12.11</td>
</tr>
<tr>
<td>Transportation cost ($/green ton) (6)</td>
<td>6.97(1)</td>
<td>6.97(1)</td>
</tr>
</tbody>
</table>

(1) Lautala et al., 2012  
(2) Harrial, 2012  
(3) Zamora, 2013  
(4) Assume the chipper will originally has a loader attached; therefore the piling cost of wood chips pile is 0.  
(5) The mobilization cost includes cost for moving chipper and loader.  
(6) Transportation cost is 9.75 $/green ton and additional $0.15/green ton per mile after 20 miles (Barnes, 2010).

### 4. Results and Discussion

#### The optimized operation system

The optimized operation system of continuously supplying Cadillac Renewable Energy with high quality biomass feedstock for 4 months is presented in Table 5. The optimized
operation system favors a shift from WCP form towards LRP form to store biomass for achieving lower MC.

At the end of July, a total of 3079.68 green tons of biomass will be harvested. An amount of 921.69 green tons of biomass will be immediately processed into wood chips and be delivered to Cadillac Renewable Energy to meet its August demand. The rest 2157.99 green tons of biomass will be stored in LRP form in the field. At the end of August, a mobile grinder needs to be moved to the harvesting site to process 671.51 green tons of 1-month air-dried logging residues into wood chips. The wood chips will then be delivered to Cadillac Renewable Energy to meet its September demand. During October and November the similar process will take place. The grinder will grind 744.49 green tons of 2-month field-stored and 741.99 green tons of 3-month field-stored biomass to meet the end-user’s monthly demand.

The split costs in each month are listed in Table 5. The highest total cost of $28,698.57 occurs in July. The chipping cost, piling cost, machine mobilization cost, and transportation cost account for 16.06%, 34.51%, 27.04%, and 22.39%, respectively. The lowest total cost of $164.96 is in August, when the only cost occurred is the holding cost for not selling the 2157.99 green tons of biomass immediately. From August to November, since there is no need for biomass piling, the total costs only include the chipping cost, the machine mobilization cost, the transportation cost, and the holding cost. From September to November, the monthly total cost varied from $9,895.48 to $10,917.60, which mainly depends on the weight of biomass processed and delivered in each month. The total cost of the four months sums up to $60,630.19. The largest component of the total cost is the transportation cost, which represents 35.40% of the total cost. The holding cost of $662.24 only accounts for 1.09% due to the relatively small amount of biomass holding.

**Comparison between optimized operation system and traditional operation system**

The optimized operation system costs the loggers $6,089.70 more compared to the traditional operation system because of the extra machine mobilization cost and the piling cost associated with establishing logging residue piles (Table 6). However, the higher cost of the optimized operation system can be offset by the additional profit of $22,204.90 from selling the higher quality biomass feedstock. As the result, the loggers can expect to earn approximately $16,115.20 more by adopting the optimized operation system.

In the optimized operation system, the total biomass required to satisfy the four-month demand is 3079.68 green tons; while in the traditional operation system, 3764.00 green tons of biomass is required to satisfy the four-month demand. The 684.32 green tons reduction in
green biomass demand is caused by the drier biomass obtained by using logging residues pile as the main storage method.

Table 5. Optimized operation system for selling biomass to Cadillac Renewable Energy

<table>
<thead>
<tr>
<th>Month</th>
<th>Storage form</th>
<th>Split Cost ($)</th>
<th>Holding cost ($)</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wood Chips Pile (WCP)</td>
<td>Logging Residues Pile (LCP)</td>
<td>Chipping cost</td>
<td>Piling cost</td>
</tr>
<tr>
<td>July</td>
<td>$\sum_{n=0}^{3} WC_n = 921.69^{(1)}$</td>
<td>$\sum_{n=0}^{3} WR_n = 2157.99^{(2)}$</td>
<td>4608.45</td>
<td>9905.16</td>
</tr>
<tr>
<td>Aug</td>
<td>WC$_0 = 921.69$</td>
<td>WR$_0 = 0.00$</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Sep</td>
<td>WC$_1 = 0.00$</td>
<td>WR$_1 = 671.51$</td>
<td>3357.53</td>
<td>0.00</td>
</tr>
<tr>
<td>Oct</td>
<td>WC$_2 = 0.00$</td>
<td>WR$_2 = 744.49$</td>
<td>3722.45</td>
<td>0.00</td>
</tr>
<tr>
<td>Nov</td>
<td>WC$_3 = 0.00$</td>
<td>WR$_3 = 741.99$</td>
<td>3709.95</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>921.69</td>
<td>2157.99</td>
<td>15398.38</td>
<td>9905.16</td>
</tr>
</tbody>
</table>

Total biomass harvested (green tons): 3079.68

Additional Profit ($): 22204.90

Total cost after Additional Profit ($) : 38425.16

Cost ($/green ton): 12.48

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(1) The total weight of green biomass is going to be stored in wood chips pile.

(2) The total weight of green biomass is going to be stored in logging residues pile.
Table 6. Traditional operation system for selling biomass to Cadillac Renewable Energy

<table>
<thead>
<tr>
<th>Month</th>
<th>Storage form</th>
<th>Split Cost ($)</th>
<th>Holding cost ($)</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wood Chips Pile (WCP)</td>
<td>Logging Residues Pile (LCP)</td>
<td>Chipping cost</td>
<td>Piling cost</td>
</tr>
<tr>
<td>July</td>
<td>$\sum_{n=0}^{3} WC_n = 3764.00^{(1)}$</td>
<td>$\sum_{n=0}^{3} WR_n = 0.00^{(2)}$</td>
<td>18820.02</td>
<td>0.00</td>
</tr>
<tr>
<td>Aug</td>
<td>WC_0=921.69</td>
<td>WR_0=0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Sep</td>
<td>WC_1=906.64</td>
<td>WR_1=0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Oct</td>
<td>WC_2=927.32</td>
<td>WR_2=0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Nov</td>
<td>WC_3=1008.35</td>
<td>WR_3=0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>3764.00</td>
<td>0.00</td>
<td>18820.02</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Total biomass harvested (green tons): 3764.00

Additional Profit ($) : 0.00

Total cost after Additional Profit ($) : 54540.36

Cost ($/green ton): 14.49

(1) The total weight of green biomass is going to be stored in wood chips pile.

(2) The total weight of green biomass is going to be stored in logging residues pile.

**Sensitivity analysis**

**Effects of transportation distance on the total cost and the optimized operation system**

In this study, transportation distance from the harvesting site to Cadillac Renewable Energy was set at 40 miles. In the sensitivity analysis, the range of the transportation distance considered is from 20 miles to 60 miles. The transportation distance has no impact on the biomass storage and transportation strategy and can only affect the total cost through changing the transportation cost. When the distance increases from 20 miles to 60 miles, the total cost after deducting additional profit rises linearly from $35,056.08 to $41,806.73 (Fig. 3.).
sensitivity analysis indicates that every 1-mile transportation distance increase will raise the total cost by $168.77. The AP earned for different transportation distance is always $22,204.90 and can cover the cost caused by the distance increase for up to 151 miles. These results suggest that the negative impact of longer transportation distance in the woody biomass supply chain can be offset by the higher biomass quality.

![Figure 3. Total cost (include AP) associated with different transportation distances](image)

**Figure 3. Total cost (include AP) associated with different transportation distances**

**Effect of biomass MC on the total cost and the optimized operation system**

The effect of biomass MC on the total cost was determined by changing the MC in a 5% increment (Fig. 4). In average, every 1% increase in biomass MC can result in $760.68 increase in total cost after deducting AP. With every 5% decrease in biomass MC of the fresh harvested biomass, the total cost after deducting AP reduced by $2976.29. On the other hand, when the biomass MC increases by 5%, 10%, and 15%, respectively, the total cost after deducting AP increases $3439.78, $4023.11, and $4772.51, respectively. This shows the higher the biomass MC is, the higher increase in total cost will be. Therefore, the harvesting operations are suggested to take place in the late spring or summer when initial biomass MC tends to be lower to reduce the total cost.

Through the increase of biomass MC, more biomass is required to satisfy the same energy demand within four month. For different biomass MC, LRP is always the preferred way to store biomass mainly because it can produce higher quality biomass feedstock (Fig. 5). A 5% decrease in biomass MC from the base case can reduce the total biomass weight demand by 203.97 green tons. When the biomass MC increases from the base case to +5%, from +5% to +10% and from +10% to +15%, the total biomass weight demand raises by 235.66 green tons, 275.54 green tons and 326.75 green tons. In average, every 1% increase in biomass MC will raise the total biomass demand by 52.1 green tons.
5. Conclusion

An optimized operation system for biomass storage and transportation was generated using computer-based linear programming technique. The simulation results indicate when using logging residue pile as the major storage form, the extra costs of $6089.70 due to piling and machine-moving operations can be offset by the $22204.90 additional profits. In addition, because of the drier biomass achieved in the optimized operation system, the biomass required to satisfy the four-month energy demand is reduced by 684.32 green tons compared to the traditional operation system.
Sensitivity analyses were conducted to evaluate the effect of transportation distance and biomass MC on the optimized operation system and the total cost. The sensitivity analysis indicates transportation distance has no effect on the storage and transportation strategy and only affects the total cost by increasing the transportation cost. Every 1-mile increase in transportation distance will raise the total cost by $168.77. The additional profit brought by higher quality biomass can offset the increased transportation cost for up to 151 miles. The changes in biomass MC affect both the optimized operation system and the total cost. This impact of biomass MC is concluded to be more significant when it is higher. In average, every 1% increase in biomass MC can result in $760.68 increase in total cost. In addition, 1% increase in biomass MC will cause 52.1 green tons increase in total biomass green weight to satisfy the four-month energy demand.

In conclusion, this computer-aided optimized operations system can effectively minimize the total cost and improve the efficiency of biomass supply chain logistics while retaining the biomass fuel quality at a higher level.

6. References:


