Strategic optimization of forest biomass supply chains with environmental and social considerations: A case study in Interior BC

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Forest industry in interior British Columbia

- 60 million hectares of BC’s land base is forested (BC Government, 2005)

- In 2005 forest products represented 40-50% of total exports (BC Government, 2005)

- BC is the largest exporter of softwood building products in the world (FII, 2010)

- Issues (Government of BC, 2009):
  - Slow recovery from US house market crisis in 2009
  - Mid-term timber supply concerns due to MPB infestation
Biomass opportunities in interior BC

Logging residues

Sawmill’s by-products

Photograph taken by Claudia Cambero, 2013
The problem...

In order to maximize the value from the forest biomass, we need to:

• Find the best product/technology
• Find the best arrangement of the forest biomass supply chain
• Consider multiple factors:
  • Economic
  • Environmental
  • Social
Previous studies - Optimization

**Strategic planning**
- Kaylen et al. (2000)
- Freppaz et al. (2004)
- Chinese and Meneghetti, (2005)
- Frombo et al. (2009a)
- Frombo et al. (2009b)
- Tittmann et al (2010)
- Parker et al. (2010)
- Feng et al. (2010)

**Tactical planning**
- Gunnarson et al. (2004)
- Kanzian et al. (2009)
- Rauch and Gronalt (2010)
- Shabani et al. (2012, 2014)

**Economy**

**Strategic planning**
- Wetterlund and Soderstrom, (2010)
- Difs et al. (2010)
- Borjesson and Ahlgren (2010)
- Rentizelas and Tatsiopoulos (2010)
- Huang et al. (2010)
- Schmidt et al. (2010a-b)

**Bi-objective planning**
- Kanzian et al. (2013)
- Perez-Fortes et al. (2014)
- You and Wang (2011)
- Santibanez et al. (2011)
- Bernardi et al. (2012)
- Giarola et al. (2011, 2013)
- Yue et al. (2013)
- Liu et al. (2014)
- Steubing et al. (2014)

**Society**

**Strategic planning**
- Yagi and Nakata. (2011)
- Leduc et al. (2011a-b)
- Elia et al. (2011)
- Kim et al. (2011a-b)
- Upadhyay et al. (2012)
- Keristead et al. (2012)
- Kong et al. (2012)
- Cambero et al. (2014)

**Multi-objective planning**
- You et al. (2012)
- Santibanez et al. (2014)
- Yue et al. (2014)
- Cucek et al. (2012)

**Environment**

**Strategic planning**
- You et al. (2012)
- Santibanez et al. (2014)
- Yue et al. (2014)

**Forest biomass SC design (up to conversion plant)**
- Kanzian et al. (2013)
- Perez-Fortes et al. (2014)
- Zamboni et al. (2009)
- You and Wang (2011)
- Santibanez et al. (2011)
- Bernardi et al. (2012)
- Giarola et al. (2011, 2013)
- Yue et al. (2013)
- Liu et al. (2014)
- Steubing et al. (2014)

**Biofuel SC design from production of agricultural and forest biomass to biofuel use**
- Cucek et al. (2012)

**Energy, food and boards from agricultural and forest biomass**
Optimize the design of a forest biomass supply chain for the production of bioenergy and other bioproducts considering economic, social and environmental objectives simultaneously

- Apply the model to a case study in interior British Columbia
Approach

MODELING FRAMEWORK

1. Single objective optimization
   - MILP

2. Environmental evaluation
   - LCA

3. Supply chain design
   - MOO + e constraint

INPUTS
- Available biomass,
- Potential value alternatives,
- Potential location of facilities,
- Estimated demand

OUTPUTS
- Analysis of trade-offs among economic, social and environmental aspects

Diagram:
- Pareto optimal

Objective 1: $NPV
Objective 2: # Jobs
Case study: Williams Lake TSA

Interior BC
One of the largest TSA in BC
Largely affected by MPB
Case study: Williams Lake TSA

- Population: 300
- Lots of biomass
- Current sawmill owned by First Nation (West Chilcotin Forest Products)
- Local electricity by diesel generators
- Interested in bio-energy
- Large potential for new products (e.g. pyrolysis, pellets)

- Population: 100
- Forestry 2nd economic activity
- Current sawmill owned by First Nation (River West Forest Products)
- 50% of electricity by diesel generators
- Interested in bio-energy and new products (e.g. pellets)

- Population: 12,000
- Forestry 1st economic activity
- Has lumber, plywood, veneer, and pellet mills.
- Has the largest biomass power plant in North America
- Limited availability of low cost logging residues
- Interested in district heat
- Potential for pellet mill expansion

Logging residues available (< $60 per dry tonne)

Figure from: for.gov.bc.ca
Supply chain alternatives

- **Set of feedstock types** \( F \)
  - Forest MPB logs
  - Forest residues
  - Sawmill chips
  - Sawmill hog fuel

- **Set of biomass sources** \( I \)
  - Forest block 1
  - Forest block 2
  - Forest block 1592
  - Anahim Lake sawmill
  - Hanceville sawmill
  - Williams Lake sawmills

- **Set of potential plant locations** \( J \)
  - Williams Lake
  - Anahim
  - Hanceville

- **Set of potential technologies & sizes** \( L \)
  - Biomass stoker boiler 2MW
  - Pyrolysis 200 or 400 odt/day
  - Gasifier+ ICE 0.5, 2 & 3 MW
  - Oil heater + ORC 0.5, 2, 3 & 5MW
  - Boiler + steam turbine 0.5, 2, 3 & 5MW
  - Pellets 15k, 30k, 45k tons/year

- **Set of potential products** \( N \)
  - Heat
  - Bio-oil
  - Power
  - Pellets

- **Set of potential markets** \( M \)
  - Williams Lake
  - Anahim
  - Hanceville
  - Europe
Formulation of Constraints

- Biomass availability over time
  \[ \sum_i u_{fijt} \leq \text{AvailableBiomass}_{f it} \quad \forall f \in F, i \in I, t \in T \]

- Technology capacity and yield
  \[ \sum_t v_{njwt} = \sum_t \text{Yield}_{njwt} \quad \forall n \in N, j \in J, l \in L, t \in T \]

- Product demand over time
  \[ \text{MinDemand}_{nmt} \leq \sum_j w_{njmt} \leq \text{MaxDemand}_{nmt} \quad \forall n \in N, m \in M, t \in T \]
  \[ \text{MinDemand}_{ojt} \leq w_{ojt} \leq \text{MaxDemand}_{ojt} \quad \forall o \in O, j \in J, t \in T \]

- Flow balances
  \[ \sum_i u_{fijt} = \sum_i u_{fjlt} \quad \forall f \in F, j \in J, t \in T \]
  \[ \sum_m w_{njmt} \leq \sum_l v_{njwt} \quad \forall j \in J, n \in N, t \in T \]

- Binary and non-negativity constraints
  \[ w_{ojt} \leq \sum l v_{ojlt} \quad \forall o \in O, j \in J, t \in T \]
  \[ q_{jlt} \geq q_{jlt-1} \quad \forall l \in L, j \in J, t \in T \]
  \[ u_{fijt}, u_{fjlt} \geq 0 \quad \forall f \in F, i \in I, j \in J, l \in L, t \in T \]
  \[ v_{njwt}, v_{ojlt} \geq 0 \quad \forall j \in J, l \in L, n \in N, o \in O, t \in T \]
  \[ w_{njmt}, w_{ojt} \geq 0 \quad \forall j \in J, m \in M, n \in N, o \in O, t \in T \]
  \[ q_{jlt} \in \{0,1\} \quad \forall l \in L, j \in J, t \in T \]
Economic objective function

\[
\text{Max NPV} = \sum_t \frac{1}{(1 + \alpha)^t-1} (\text{TotalRevenue}_t - \text{TotalCost}_t) \]

\[
\text{TotalRevenue}_t = \sum_{nm} \left( \text{BiofuelPrice}_{nm} \cdot \sum_j w_{nj} \right) + \sum_{oj} \left( \text{BioenergyPrice}_{oj} \cdot \sum_i w_{oi} \right)
\]

\[
\text{TotalCost}_t = \sum_{fi} \left( \text{BiomassCost}_{fi} \cdot \sum_j u_{fij} \right) + \sum_{fij} \left( \text{BiomassTransportCost}_{fij} \cdot u_{fij} \right) + \sum_{ij} \left( \text{FixedCost}_{ij} \cdot \sum_j q_{ij} \right) + \sum_l \left( \text{VariableCost}_{il} \cdot \sum_f u_{fl} \right) + \sum_{nmj} \left( \text{BiofuelTransportCost}_{nj} \cdot w_{nmj} \right)
\]

- Revenue from products
- Biomass purchase/ collection
- Biomass transportation
- Capital and production
- Biofuel transportation
Economically-optimal solution (20 years)

Optimal NPV: CAD$557 million

**Anahim Lake**
- Biomass boiler + steam turbine
- ELECTRICITY ONLY (5 MW), $t_1$

**Hanceville**
- Biomass boiler + steam turbine
- ELECTRICITY ONLY (0.5 MW), $t_1$
- Pyrolysis plant (400 odmt/day), $t_1$

**Williams Lake**
- Biomass boiler (2MW), $t_1$
- Pyrolysis plant (200 odmt/day), $t_{11}$
## Economically-optimal solution (sensitivity)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Base Case</th>
<th>-20%</th>
<th>+20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bio-oil price</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio-oil demand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity price in Hanceville</td>
<td>$0.095</td>
<td></td>
<td>$0.285</td>
</tr>
<tr>
<td>Electricity price in Anahim Lake</td>
<td>$0.095</td>
<td></td>
<td>$0.285</td>
</tr>
<tr>
<td>Heat price in Anahim Lake</td>
<td>$0.095</td>
<td></td>
<td>$0.285</td>
</tr>
<tr>
<td>Cost of harvesting residues</td>
<td>$20</td>
<td></td>
<td>$0</td>
</tr>
<tr>
<td>Total available biomass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat demand in Anahim Lake</td>
<td></td>
<td>-20%</td>
<td>+20%</td>
</tr>
<tr>
<td>Cost of sawmill wastes</td>
<td>chips $50, hog fuel $20</td>
<td></td>
<td>chips $0, hog fuel $0</td>
</tr>
<tr>
<td>Pellets price</td>
<td>$135</td>
<td></td>
<td>$150</td>
</tr>
<tr>
<td>Pellet demand</td>
<td></td>
<td>-20%</td>
<td>+20%</td>
</tr>
</tbody>
</table>

**Percentage of variation with respect to base case solution**
## Economically-optimal solution (sensitivity)

<table>
<thead>
<tr>
<th>Site</th>
<th>Technology &amp; size</th>
<th>Bio-oil demand</th>
<th>Bio-oil price</th>
<th>Electricity price</th>
<th>Heat demand</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anahim Lake</td>
<td>5MW Steam</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Anahim Lake</td>
<td>3MW Steam CHP&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Anahim Lake</td>
<td>5MW ORC&lt;sup&gt;b&lt;/sup&gt; CHP</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Hanceville</td>
<td>5MW Steam</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Hanceville</td>
<td>0.5MW Steam</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Hanceville</td>
<td>400 dt pyrolysis</td>
<td>1</td>
<td>X</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Hanceville</td>
<td>600 dt pyrolysis</td>
<td>1</td>
<td>X</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Williams Lake</td>
<td>2MW Stoker boiler</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Williams Lake</td>
<td>200 dt pyrolysis</td>
<td>X</td>
<td>X</td>
<td>16</td>
<td>11</td>
<td>16</td>
</tr>
</tbody>
</table>

<sup>a</sup> Combined Heat and Power, <sup>b</sup> Organic Rankine Cycle

Other objective functions - formulation

Economic coefficients quantify the economic performance

- Biomass purchase/collection costs
- Biomass transportation costs
- Production costs
- Biofuel transportation costs
- Products sold

Environmental coefficients quantify GHG emissions & savings

- Biomass purchase/collection emissions
- Biomass transportation emissions
- Production emissions
- Biofuel transportation emissions
- Use & avoided emissions

Social coefficients quantify number of jobs created

- Biomass purchase/collection labor hours
- Biomass transportation labor hours
- Production labor hours
- Biofuel transportation labor hours

Life cycle GHG emissions

washingtondnr.wordpress.com; wellonsfei.ca/en/is-biomass-green.aspx; Microsoft Clip Art; biv.com; paperadvance.com; cfs.nrcan.gc.ca
Life cycle GHG emissions

ISO 14040: 2006

Supply chain alternatives:

- 3 plant sites
- 3 sawmill centers
- 1592 forest blocks
- 4 biomass types
- 21 technologies and capacities
- 4 products
- 4 markets
Preliminary findings:

• The optimal use of forest residues could generate profit for forest-dependent communities in British Columbia:
  • Electricity production from forest biomass is already competitive with current off-grid sources (diesel)
  • The best alternative for electricity production is the installation of biomass boilers with steam turbines for the production of electricity only
  • The overall costs associated with fast pyrolysis would be low in the region → there is an opportunity for high profit if the market for bio-oil develops
• In addition to economic benefits, the optimal use of forest residues could generate GHG emission savings compared with the current open-burning of residues and current energy sources
Next steps

• Incorporation of GHG emission coefficients into optimization model (in progress).

• Incorporation of job creation coefficients into optimization model.

• Development and solution of a multi-objective optimization of the forest residue supply chain considering economic, environmental and social objectives.
Acknowledgements
Questions?
References


• Bernardi, A., Giarola, S., Bezzo, F., 2012. Optimizing the economics and the carbon and water footprints of bioethanol supply chains. Biofuels, Bioproducts and Biorefining. 6, 656-672


• Danon, G., Furtula, M., & Mandić, (2012) M. Possibilities of implementation of CHP (combined heat and power) in the wood industry in Serbia. Energy, (0)


References

- Kanzian et al. (2013)


References


