Integrated Biomass Supply and Logistics (IBSAL)

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Biomass and Bioenergy Research Group (BBRG)

- UBC biomass gasifier
- Biomass engineering lab
- Biomass logistics modeling
- Pellet mill
- Biomass dryer
- Hammer mill
- Wood pellet storage
Woody and Herbaceous Pellet Samples at BBRG

Aspen  Douglas fir  Switchgrass  Corn Stover  Miscanthus  Wheat straw
• A decision-making support tool to understand the complexity and dynamics of the biomass supply chain
  - Harvest and collection
  - Storage
  - Transportation and handling
  - Preprocessing (e.g. densification, drying, grinding)

Meet **Quality**, **Quantity** and **Cost** specifications of the biorefinery
IBSAL strengths

- **Dynamic tool**: consideration of variability and uncertainty in the input parameters such as weather data, yield and moisture content.

- **Development of engineering equations** (for design of unit operations and to monitor changes in the system such as moisture content, dry matter loss, field working condition and equipment performance): this strength enables IBSAL to provide accurate information on the performance of the entire biomass supply chain in terms of cost, quantity and quality.

- **Database**: the IBSAL database has been developed gradually in the last 10 years and has detailed information on the equipment properties and their engineering economics: harvest and collection equipment, handling equipment, transportation equipment, preprocessing equipment, conveyors and storage configurations.
Recent Industrial Projects in USA and Canada

- Fractionation, drying and pelletization of multiple biomass streams
- Logistics of wheat straw for a proposed cellulosic ethanol plant
- Logistics of corn stover for the OPG power facility in Lambton
- Logistics of Miscanthus for the a cellulosic ethanol plant in North Carolina
- Risk assessment of the corn stover logistics for a cellulosic sugar plant in Sarnia
- Optimizing the field operations for poplar
- Optimizing the willow harvest operations
- Feasibility study of Biojet Production
- Logistics of woody biomass and pellet distribution for two pellet plants
- Feasibility Study of cofiring wood pellets with coal
- Logistical resources required for a cellulosic ethanol plant in Iowa
- Biomass characteristics of the UBC Gasification facility
- Feasibility Study of cofiring wood pellets with coal
IBSAL framework

Input Data (IBSAL- Excel file)

- Daily Weather Data
  - Average temperature
  - Snow
  - Rain
  - Relative humidity
  - Evaporation

- Harvest Schedule
  Length of harvest window
  Number of working days

- Crop Data
  - Historical biomass yield
  - Yield to be deducted for conservation
  - Harvest moisture content

- Field Data
  - Total crop supply area
  - Distance to the side of farm

- Equipment Data
  - Equipment width
  - Speed
  - Horsepower
  - Hourly cost of equipment

- Storage Data
  - Number and size of storage sites
  - Distance from farm to storage
  - Distance from storage to final destination

Simulation (IBSAL- ExtendSim file)

- Simulating all operations required to deliver biomass from farm lands to the conversion plant
- Mathematical equations calculating the operational performance of equipment
- Mathematical equations calculating moisture content and dry matter loss

Outputs (IBSAL- Excel file)

- Economic output:
  - Custom Cost per ton of biomass
  - Ownership Cost per ton of biomass
- Energetic and environment output:
  - Energy Input
  - CO₂ Emission
- Biomass recovery:
  - Dry matter loss
  - Net collected yield
- Resource output:
  - Number of days to complete each operation
  - Number of required machines and workforce
  - Utilization rate for machineries
  - The harvested area

Flow of information to and from IBSAL
Given the dynamics, stochastic and complex nature of biomass supply chains, the main concern is the **robustness** of the supply chain instead of optimality.

To Develop a robust supply chain, sources of variability are first identified, their impacts are quantified and the elements of supply chain are designed and planned according to the magnitude of variability in the entire system.

**Why simulation in IBSAL?**
IBSAL- Baling and chopping scenarios

• Two existing scenarios to harvest and collect agricultural biomass are modeled in IBSAL including baling and chopping.
• The following decisions are made in IBAL for both baling and chopping scenarios:
  - Location of bio-processing facility
  - Location of storage sites
  - Number of biomass suppliers to contract and their location
  - Ownership and custom operating costs ($/dry tonne)
  - Biomass inventory planning
  - Truck planning and scheduling
  - Number of required logistics equipment
  - Daily flow of biomass in the entire biomass supply chain
  - Dry matter loss monitoring
  - Moisture content monitoring
  - Biomass delivered cost ($/dry tonne)
  - Equipment energy consumption and its associated CO$_2$ emissions
Baling scenario modeled in IBSAL

Figure 1. Base case biomass logistics system- bale scenario.

- The bale scenario is developed based on the existing agricultural machinery used in the three pioneering cellulosic ethanol projects in the USA.
- This scenario is considered for corn stover, wheat straw, miscanthus and switchgrass.
Equipment used in baling scenario

- Corn stover chopper/shredder
- Baler
- Bale collector/stacker
- Self-propelled windrower-Miscanthus and switchgrass
- Tractor (180-220hp)
- Truck and flatbed trailer
- Telescopic loader

Snapshot of baling scenario in IBSAL
The chop scenario is developed based on the existing agricultural machinery used to harvest biomass crops and forage crops.

This scenario is considered for miscanthus, switchgrass, willow and poplar.
Equipment used in chopping scenario

Forage harvester

Dump Wagon

Tractor (180-220hp)

Agricultural telehandler/Wheel loader

Dump Truck/Silage truck

18-wheeled chips truck and trailer
Example of chopping harvest system in IBSAL
Snapshot of chopping scenario in IBSAL
Examples of modules developed in IBSAL
### Harvest and collection

#### Input data
- Harvest season
- Working hours
- Daily biomass demand
- Moisture content
- Biomass removal rate
- Farm size
- Supply radius
- Weather condition
- Equipment data

#### Output data
- Baling cost ($/dt)
- Number of equipment
- Number of bales and bale density
- Utilization rate
- Dry matter loss
- Energy input and the associated emission

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**Baling module in IBSAL**

Photo: [http://www.us.all.biz/large-square-balers-hesston-2100-series-g84883#.Vfc0lxHBzRY](http://www.us.all.biz/large-square-balers-hesston-2100-series-g84883#.Vfc0lxHBzRY)
Storage

Input data

- Location of farms and the biorefinery
- Annual biomass demand
- Moisture content
- Fire code
- Bale type and size
- Quality specification
- Weather condition

Output data

- Storage cost ($/dt)
- Number and size of storage sites
- Storage configuration
- Utilization rate
- Dry matter loss
- Inventory planning and scheduling

Storage module in IBSAL

Photo: http://vitalbypoet.com/stories/it-all-starts-with-biomass

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BIOMASS.UBC.CA
Transportation

**Input data**
- Location of storage sites and the biorefinery
- Daily biomass demand
- Moisture content
- Truck configuration
- Road class

**Output data**
- Transportation cost ($/dt)
- Number of trucks
- Truck scheduling
- Utilization rate
- Energy input and the associated emission

**Transportation module in IBSAL**

Photo: www.visualphotos.com
Pre-processing

Input data
- Quality specification of the conversion reactor
- Quality of delivered biomass (moisture content, particle size, ash content,..)

Output data
- Pre-processing cost ($/dt)
- Type of preprocessing (grinding, drying,..)
- Utilization rate
- Dry matter loss
- Energy input and the associated emission

Pre-processing module in IBSAL

Photo: Sokhansanj, 2015- Pricing INL-PDU operations
Examples of input data in IBSAL
Examples of Variable Input Parameters

- biomass yield
- harvest window
- harvest moisture content
- bale bulk density
- farm participation rate
- dry matter loss
- equipment capacity and efficiency
- machine breakdown and repair times
- winding factor and road transportation times
## Variability in logistics data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>Ave.: 44.4, S.D.: 2.2</td>
</tr>
<tr>
<td>Bulk density-willow chips (kg/m³)</td>
<td>[170, 260]</td>
</tr>
<tr>
<td>Failure interval time (h)</td>
<td>Exp (10h)</td>
</tr>
<tr>
<td>Repair interval time (h)</td>
<td>Exp (1h)</td>
</tr>
<tr>
<td>Biomass no collected and left on the field (%) (of standing biomass)</td>
<td>[4, 9]</td>
</tr>
<tr>
<td>Turn time at headlands (min)</td>
<td>[0.5, 4.5+]</td>
</tr>
<tr>
<td>Percentage of total unplanted area in a parcel (%)</td>
<td>[13, 28]</td>
</tr>
<tr>
<td>Harvester field speed (km/h)</td>
<td>[2, 9]</td>
</tr>
<tr>
<td>Travel speed (km/h)- collection equipment</td>
<td>Cane wagon: Ave. 5.8, S.D. 2.4</td>
</tr>
<tr>
<td></td>
<td>Dump cart: Ave. 3.9, S.D.: 1.2</td>
</tr>
<tr>
<td></td>
<td>Forage wagon: Ave. 5.8, 2.4</td>
</tr>
<tr>
<td></td>
<td>Silage truck: Ave.: 14.6, 3.1</td>
</tr>
<tr>
<td></td>
<td>18-wheeled truck: Ave. 64.3, S.D. 28.1</td>
</tr>
</tbody>
</table>
### Input Data - Harvester

<table>
<thead>
<tr>
<th>Equipment characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase price (US$)</td>
<td>480,000 (harvester + 130 FB coppice header)</td>
</tr>
<tr>
<td>Economic life (yr)</td>
<td>7</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>510</td>
</tr>
<tr>
<td>Operational width (m)</td>
<td>2.29</td>
</tr>
<tr>
<td>Field speed (km/h)</td>
<td>[2, 9]</td>
</tr>
<tr>
<td>Biomass no collected and left on the field after harvesting operations (% of standing biomass)</td>
<td>[4, 9]</td>
</tr>
<tr>
<td>Turn time at headlands (min)</td>
<td>[0.5, 4.5+]</td>
</tr>
<tr>
<td>Set time to failure</td>
<td>Exp (10h)</td>
</tr>
<tr>
<td>Set time to repair</td>
<td>Exp (1h)</td>
</tr>
<tr>
<td>Willow chips- moisture content at harvest time (wet basis, %)</td>
<td>Ave.: 44.4 S.D.: 2.2</td>
</tr>
<tr>
<td>Bulk density of harvested wood chips (kg/m³)</td>
<td>[170, 260]</td>
</tr>
<tr>
<td>Percentage of total unplanted area in a parcel (%) (headlands, road access, un-cleared obstructions, failed establishment, wet areas, ditches etc.)</td>
<td>[13,28]</td>
</tr>
</tbody>
</table>
## Input Data - Collection and transportation equipment

<table>
<thead>
<tr>
<th>Equipment data</th>
<th>Collection and transportation equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cane wagon + tractor</td>
</tr>
<tr>
<td><strong>Purchase price (US$)</strong></td>
<td>Wagon: 40,500, Tractor: 115,000</td>
</tr>
<tr>
<td><strong>Economic life (yr)</strong></td>
<td>Wagon: 5, Tractor: 12</td>
</tr>
<tr>
<td><strong>Tractor power (hp)</strong></td>
<td>105</td>
</tr>
<tr>
<td><strong>Load volume (m³)</strong></td>
<td>34</td>
</tr>
<tr>
<td><strong>Travel speed-full (km/h)</strong></td>
<td>Ave.: 5.8, S.D.: 2.4</td>
</tr>
</tbody>
</table>
## Input Data - Collection and transportation equipment

<table>
<thead>
<tr>
<th>Equipment data</th>
<th>Collection and transportation equipment</th>
<th>18-wheeled chip trailer + truck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cane wagon + tractor</td>
<td>Silage truck</td>
</tr>
<tr>
<td></td>
<td>Dump cart + tractor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forage wagon + tractor</td>
<td></td>
</tr>
<tr>
<td>Travel speed-empty (km/h)*</td>
<td>Ave.: 8.2 S.D.: 2.7</td>
<td>Ave.: 8.2 S.D.: 2.7</td>
</tr>
<tr>
<td>Unload time (min)</td>
<td>[2.5, 4]</td>
<td>[2.5, 4]</td>
</tr>
<tr>
<td>Dry matter loss (%)</td>
<td>[0, 2]</td>
<td>[0, 2]</td>
</tr>
<tr>
<td>Winding factor</td>
<td>[1, 1.2]</td>
<td>[1, 1.2]</td>
</tr>
<tr>
<td>Set time to failure</td>
<td>Exp (10h)</td>
<td>Exp (10h)</td>
</tr>
<tr>
<td>Set time to repair</td>
<td>Exp (0.25hr)</td>
<td>Exp (0.25hr)</td>
</tr>
</tbody>
</table>
Examples: Outputs of IBSAL
Harvest area (ac) based on the size of the biorefinery

Small-scale biorefinery scenario (175 dry tonne/day)

Mid-scale biorefinery scenario (520 dry tonne/day)

Large-scale biorefinery scenario (860 dry tonne/day)
Major factors impacting the number of agricultural machinery to mobilize biomass in commercial quantities

- Biorefinery size
- Biomass availability and distribution in the supply area
- Daily working hours
- Number of required agricultural machinery
- Harvest window and number of working days
- Field capacity of the machinery
## Number of logistics equipment and workforce

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Small-scale biorefinery scenario (175 dry tonne/day)</th>
<th>Mid-scale biorefinery scenario (520 dry tonne/day)</th>
<th>Large-scale biorefinery scenario (860 dry tonne/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of machines</td>
<td>Economic value ($)</td>
<td>Number of operators</td>
</tr>
<tr>
<td>Cornstalk shredder</td>
<td>7</td>
<td>245,000</td>
<td>-</td>
</tr>
<tr>
<td>Square baler</td>
<td>7</td>
<td>980,000</td>
<td>-</td>
</tr>
<tr>
<td>Bale collector/stacker</td>
<td>7</td>
<td>1,750,000</td>
<td>7</td>
</tr>
<tr>
<td>Tractor (185-220 hp)</td>
<td>14</td>
<td>2,800,000</td>
<td>14</td>
</tr>
<tr>
<td>Telescopic bale loader-</td>
<td>3</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>roadside of corn fields</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>53-ft flatbed trailer truck-</td>
<td>9</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>roadside of corn fields</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telescopic bale loader-</td>
<td>3</td>
<td>27,0000</td>
<td>3</td>
</tr>
<tr>
<td>intermediate storage site</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>53-ft-flatbed truck-intermediate storage site</td>
<td>3</td>
<td>58,5000</td>
<td>3</td>
</tr>
<tr>
<td>Telescopic bale loader-</td>
<td>1</td>
<td>90,000</td>
<td>1</td>
</tr>
<tr>
<td>Cellulosic sugar facility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>54</td>
<td>6,720,000</td>
<td>37</td>
</tr>
</tbody>
</table>
## Storage size and inventory level

<table>
<thead>
<tr>
<th>Biorefinery scenario</th>
<th>Small-scale biorefinery scenario (175 dry tonne/day)</th>
<th>Mid-scale biorefinery scenario (520 dry tonne/day)</th>
<th>Large-scale biorefinery scenario (860 dry tonne/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum inventory (dt)</td>
<td>45,563</td>
<td>143,564</td>
<td>228,759</td>
</tr>
<tr>
<td>Number of stored bales</td>
<td>92,596</td>
<td>291,763</td>
<td>464,903</td>
</tr>
<tr>
<td>Stack configuration (bales)</td>
<td></td>
<td>6 high, 6 wide and 60 long</td>
<td></td>
</tr>
<tr>
<td>Number of stacks</td>
<td>47</td>
<td>136</td>
<td>216</td>
</tr>
<tr>
<td>Clearance between stacks (m)</td>
<td></td>
<td>30.5</td>
<td></td>
</tr>
<tr>
<td>Total storage footprint (ac)</td>
<td></td>
<td>42.6</td>
<td>144.4</td>
</tr>
</tbody>
</table>

### Graph

- SS
- MS
- LS

**Y-axis:** Stover inventory at the storage site (dt)

**X-axis:** Simulation day

- 0
- 30
- 60
- 90
- 120
- 150
- 180
- 210
- 240
- 270
- 300
- 330
- 360

**Legend:**

- SS
- MS
- LS
## Biomass delivered costs - Average values

<table>
<thead>
<tr>
<th>Cost component ($/dt)</th>
<th>Small-scale biorefinery scenario (175 dry tonne/day)</th>
<th>Mid-scale biorefinery scenario (520 dry tonne/day)</th>
<th>Large-scale biorefinery scenario (860 dry tonne/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient replacement</td>
<td>12.05</td>
<td>12.05</td>
<td>12.05</td>
</tr>
<tr>
<td>Shred and windrow</td>
<td>7.42</td>
<td>7.59</td>
<td>7.77</td>
</tr>
<tr>
<td>Bale</td>
<td>17.36</td>
<td>17.66</td>
<td>17.68</td>
</tr>
<tr>
<td>Bale collection/stack at the roadside</td>
<td>8.66</td>
<td>8.92</td>
<td>8.98</td>
</tr>
<tr>
<td>Load at the roadside</td>
<td>2.11</td>
<td>2.28</td>
<td>2.30</td>
</tr>
<tr>
<td>Transportation to the intermediate storage</td>
<td>26.62</td>
<td>34.39</td>
<td>42.81</td>
</tr>
<tr>
<td>Load &amp; unload at the intermediate storage</td>
<td>1.66</td>
<td>1.70</td>
<td>1.77</td>
</tr>
<tr>
<td>Intermediate storage</td>
<td>9.09</td>
<td>9.37</td>
<td>9.80</td>
</tr>
<tr>
<td>Transportation to the bio-conversion facility</td>
<td>14.32</td>
<td>14.12</td>
<td>14.04</td>
</tr>
<tr>
<td>Unload at the facility</td>
<td>1.10</td>
<td>1.08</td>
<td>1.06</td>
</tr>
<tr>
<td><strong>Total delivered cost</strong></td>
<td><strong>82.09</strong></td>
<td><strong>87.49</strong></td>
<td><strong>93.75</strong></td>
</tr>
</tbody>
</table>
## Biomass delivered costs

<table>
<thead>
<tr>
<th>Biorefinery scenario</th>
<th>Small-scale biorefinery scenario (175 dry tonne/day)</th>
<th>Mid-scale biorefinery scenario (520 dry tonne/day)</th>
<th>Large-scale biorefinery scenario (860 dry tonne/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum observed value ($/dt)</td>
<td>92.38</td>
<td>101.08</td>
<td>107.79</td>
</tr>
<tr>
<td>Average observed value ($/dt)</td>
<td>82.09</td>
<td>87.49</td>
<td>93.75</td>
</tr>
<tr>
<td>Minimum observed value ($/dt)</td>
<td>72.76</td>
<td>77.24</td>
<td>79.19</td>
</tr>
<tr>
<td>Standard deviation ($/dt)</td>
<td>3.97</td>
<td>4.56</td>
<td>5.18</td>
</tr>
<tr>
<td>Confidence interval</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Probability of achieving the target delivered cost</td>
<td>45.5%</td>
<td>9.2%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>
In addition to the average costs, other information that can be extracted from the IBSAL are the standard deviation, percentiles to quantity the deviation from the target delivered cost and worse and best delivered costs.
Biomass delivered costs

Target delivered cost ($81.33/dt) to meet the expected Return on Investment of 15%

Small-scale biorefinery scenario (175 dry tonne/day)

Mid-scale biorefinery scenario (520 dry tonne/day)

Large-scale biorefinery scenario (860 dry tonne/day)
Max inventory of 189,240 dt is observed at the end of harvest season. In the baseline scenario, this level of inventory is stored at the roadside of fields. This inventory can also be stored in the intermediate storage sites to facilitate the transportation operations.
Number of contracted farms

Distance range (km)

- 15-30: 87 farms
- 30-45: 111 farms
- 45-60: 114 farms
- 60-85: 285 farms
- 85-100: 26 farms
- 100-115: 25 farms
Energy Input (MJ/dt) - Logistics operations

- Baling: 102.31 MJ/t
- Infield transportation: 52.65 MJ/t
- Loading: 23.21 MJ/t
- Road transportation: 471.82 MJ/t
- Unloading: 23.74 MJ/t
- Grinding: 269.38 MJ/t
CO2 emissions (kg/dt) - Logistics operations

- Baling: 7.02 kg/dt
- Infield transportation: 3.59 kg/dt
- Loading: 1.58 kg/dt
- Road transportation: 30.34 kg/dt
- Unloading: 1.63 kg/dt
- Grinding: 27.07 kg/dt
Sensitivity analysis

- Bale bulk density (kg)
- Custom cost of truck ($/hr)
- In-field transporter efficiency (%)
- Custom cost of in-field transporter ($/hr)
- Truck efficiency (%)
- Biomass yield (t/ha)
- Storage DMLs (%)
- Grinder efficiency (%)
- Custom cost of trailer ($/hr)
- Baling capacity (tonne/hr)
- Custom cost of grinding ($/hr)
- Baling efficiency (%)
- Loading efficiency (%)
- Baling DMLs (%)

Change in the delivery cost

-10%  -8%  -6%  -4%  -2%  0%  2%  4%  6%  8%  10%