From tree assortments to an engineering biomaterial in industry

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Switch from fossils to a biobased economy!

...from one **material** to another one...

...from “black-box logs” to defined **engineering material**...
<table>
<thead>
<tr>
<th></th>
<th>Crude Oil</th>
<th>Wood (dry matter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>84%</td>
<td>45-50%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>14%</td>
<td>6%</td>
</tr>
<tr>
<td>Sulfur</td>
<td>1-3%</td>
<td>≤0.05%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>≤1%</td>
<td>≤0.5%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>≤1%</td>
<td>38-42%</td>
</tr>
<tr>
<td>Metals</td>
<td>≤1%</td>
<td>≤0.5%</td>
</tr>
<tr>
<td>Salts</td>
<td>≤1%</td>
<td></td>
</tr>
</tbody>
</table>

Trees not only wood
There are many concepts...
Meeting of the FAO Advisory Committee on Sustainable Forest-based Industries, June 2014.

Discussion paper - “Editor”: SBT
Important product areas 2014 (cf. FAO)

- Gasification, torrification and fermentation of biomass
- Biomass-based polymers/plastics and composites
- Nano-technology in general
- Bi-products from pulp- and paper industry
- Extractives from wood and bark
- Degradable packaging
- Valorisation of waste

No "golden egg"...
A chemicals-driven biorefinery

EuroBioRef biorefineries are **chemicals/materials-driven**

- Best part of the crops: High value chemicals and other products
- Residues: Production of energy
How do other sectors and disciplines define materials?

Cf. metal and plastics sector
Characterisation of chemical and physical structure

Today: Very high resolution

http://www.matthey.com/
# Material Property Tables

## AC6091 Boron Nitride (BN) Powder

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density</td>
<td>1.00 g/cc</td>
</tr>
<tr>
<td>Particle Size</td>
<td>10 µm min</td>
</tr>
<tr>
<td></td>
<td>125 µm max</td>
</tr>
<tr>
<td>Specific Surface Area</td>
<td>1.4 m²/g</td>
</tr>
</tbody>
</table>

### Descriptive Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.05%</td>
</tr>
<tr>
<td>Color</td>
<td>White</td>
</tr>
<tr>
<td>Crystal Type</td>
<td>Hexagonal (Graphitic)</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.3%</td>
</tr>
<tr>
<td>Sol. Borate</td>
<td>0.1%</td>
</tr>
</tbody>
</table>
Failed component

Photo

SEM-image

Micrograph

Links in the material – products chain

Metals Technology Centre http://www.mmtc.co.za/
How do we do in the forest sector (in Sweden)?
Assortments and identification of properties today (Sweden)

Timber (trend: ”Pine” and ”spruce”)

• **Log-wise** (volume under bark).
• Length & top diameter, **species** & some quality measures, bark type.

Pulp wood (deciduous..., conifers...)

• Volume (m3fub) or weight of truck **piles**, log samples
• **Judging of** ”air” and bark.

Bioenergy

• **M³** or **tons**, calculations to MWh from **judged moisture content**.
• Samples.

Matching...?
Assortments in the forest

Thunell, B. & Perem E. 1952. Svenskt trä (Swedish wood)

- Saw timber: 5 subclasses
- Veneer & plywood: subclasses
- Pulpwood: 5x2 subclasses
- Props
- Cross ties
- Telephone poles
- Power line poles
- Dutch poles
- Chevrons
- Beams
- Billets
- Firewood: 6 subclasses

1952 (often species-wise)

Today

Very few assortments

Some attempts:

Classifications by harvester.
Trend: Owners with industry wants to reduce assortment prices – Owners without industry wants to increase assortment prices...!

Trend: We characterize during or in-between processes...!
Saw mills: CT-scanning 3D-image (bark and knots)
Image of densities

SCA Shape 4.2014
Battens, boards, planks and timber joists/studs and beams: classified according to its strength by visual or machine grading.

Spectroscopic & ultrasonic characterisation.
Fibres/tracheids
Microfibril angle

Basic properties of fibres/tracheids

**Size**
- Length
- Width
- Cell wall thickness
- Coarseness

**Shape**
- Specific surface
- Fibrillation
- Curl

**Cell wall**
- Flexibility
- Swelling
- Pore volume
- Specific volume
- Micro compressions

**Surface**
- Chemical comp.
- ESCA
- Fibril angles

The diagram shows the relationship between length-weighted fibre length and tear index, as well as the relationship between Kajaani Cell wall thickness and tensile index. The correlation coefficient for the tear index versus fibre length is $R = 0.93$.

Further **biomaterial** challenges in the forest-based bioeconomy?
Market potential (5 & 10 år)

Potential (0-10) for different parts of the tree

Most parts of importance!

“Trees/wood: an enormous, renewable raw material resource for the production of both energy, chemicals a.o. biobased products”

Commercial reality or myth?
Big variation between species/trees (needles, leaves, etc.)
Big variation within trees

- Outer bark
- Phloem
- Cambium
- Sapwood
- Heartwood
Big variation within trees

Wood density

Microfibril angle

Wood stiffness

Radial diameter

Wall thickness

Tangential diameter

Ring widths and orientations

Ray orientations

Fibre orientations
<table>
<thead>
<tr>
<th>Constituent (%)</th>
<th>Scots pine</th>
<th>Spruce</th>
<th>Eucalyptus</th>
<th>Birch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>40</td>
<td>40</td>
<td>45</td>
<td>41</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>29</td>
<td>30</td>
<td>19</td>
<td>32</td>
</tr>
<tr>
<td>Lignin</td>
<td>28</td>
<td>28</td>
<td>31</td>
<td>22</td>
</tr>
<tr>
<td>Extractives</td>
<td>3.5</td>
<td>2.1</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Constituent</td>
<td>Scots Pine (Pinus sylvestris)</td>
<td>Spruce (Picea glauca)</td>
<td>Eucalyptus (Eucalyptus camaldulensis)</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-------------------------------</td>
<td>-----------------------</td>
<td>--------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Cellulose (%)</td>
<td>40</td>
<td>39.5</td>
<td>45.0</td>
<td></td>
</tr>
<tr>
<td>Hemicellulose</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Glucomannan (%)</td>
<td>16.0</td>
<td>17.2</td>
<td>3.1</td>
<td></td>
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<tr>
<td>- Glucuronoxylan (%)</td>
<td>8.9</td>
<td>10.4</td>
<td>14.1</td>
<td></td>
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<tr>
<td>- Other polysaccharides (%)</td>
<td>3.6</td>
<td>3.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Lignin (%)</td>
<td>27.7</td>
<td>27.5</td>
<td>31.3</td>
<td></td>
</tr>
<tr>
<td>Total extractives (%)</td>
<td>3.5</td>
<td>2.1</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>Name</td>
<td>Number above zero</td>
<td>Maximum concentration (mg/g)</td>
<td></td>
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<td>--------</td>
<td>-----------------------------------------</td>
<td>-------------------</td>
<td>-----------------------------</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Hexadecanoic acid</td>
<td>120</td>
<td>0.54</td>
<td></td>
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<tr>
<td>2</td>
<td>Heptadecanoic acid</td>
<td>118</td>
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<tr>
<td>3</td>
<td>Linolenic acid</td>
<td>92</td>
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<td>4</td>
<td>9,12-Octodecaadienoic acid</td>
<td>113</td>
<td>0.89</td>
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<tr>
<td>5</td>
<td>Oleic acid</td>
<td>120</td>
<td>1.26</td>
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<tr>
<td>6</td>
<td>Nonanoic acid</td>
<td>40 *</td>
<td>0.06</td>
<td></td>
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<tr>
<td>7</td>
<td>Linolenic acid, anteiso</td>
<td>73 *</td>
<td>0.64</td>
<td></td>
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<tr>
<td>8</td>
<td>Octadecanoic acid</td>
<td>57 *</td>
<td>1.43</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Octanoic acid</td>
<td>19 **</td>
<td>0.04</td>
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<tr>
<td>10</td>
<td>Hexadecanoic acid, anteiso</td>
<td>37 **</td>
<td>0.07</td>
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<tr>
<td></td>
<td></td>
<td>26 **</td>
<td>0.06</td>
<td></td>
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<tr>
<td>11</td>
<td>7-Oxodehydroabietic acid</td>
<td>106</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Pimaric acid</td>
<td>119</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Isopimaric acid</td>
<td>110</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Docosanoic acid</td>
<td>20 **</td>
<td>0.06</td>
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</tr>
<tr>
<td>15</td>
<td>Docosanoic acid, anteiso</td>
<td>30 **</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Docosanoic acid, anteiso</td>
<td>32 **</td>
<td>0.21</td>
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<tr>
<td>17</td>
<td>Tricosanoic acid</td>
<td>5 **</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>11-cis-Abietic acid</td>
<td></td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Eicosanoic acid</td>
<td></td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Docosanoic acid</td>
<td></td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Docosanoic acid, anteiso</td>
<td></td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Pimaric acid</td>
<td></td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Pimaric acid, anteiso</td>
<td>8&gt;</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Isopimaric acid</td>
<td>119</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Isopimaric acid, anteiso</td>
<td>80</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Dehydroabietic acid</td>
<td>121</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Abietic acid</td>
<td>110</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>7-Oxodehydroabietic acid</td>
<td>106</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Pimaric acid, anteiso</td>
<td>54 *</td>
<td>2.87</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Dehydroabietic acid, anteiso</td>
<td>42 *</td>
<td>2.06</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Isopimaric acid, anteiso</td>
<td>20 **</td>
<td>0.79</td>
<td></td>
</tr>
</tbody>
</table>

* Fewer than 80 measurements with nonzero conc.
** Fewer than 40 measurements with nonzero conc., therefore not considered in subsequent analyses.

"All" properties in each tree!
$M^3$ of wood (log) needed per $m^3$ of product

- Wood for heating & electricity
- Wood pellets
- Building wood
- Ethanol
- Transportation fuels
- Tall oil
- Tall oil diesel

Energy in wood

Net calorific value (MJ/kg wet basis) vs. Water content (%) for Fresh weight.
More of "material sciences" in the forest sector?

Property tables?

Models on material properties for machine vision?
American Red Maple as engineering material – Property table

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.490 g/cc</td>
</tr>
<tr>
<td>Hardness, Wood Indentation</td>
<td>2700 N</td>
</tr>
<tr>
<td>Tensile Strength, Ultimate</td>
<td>4.00 MPa</td>
</tr>
<tr>
<td>Modulus of Rupture</td>
<td>0.0538 GPa</td>
</tr>
<tr>
<td>Flexural Yield Strength</td>
<td>28.3 MPa</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>9.79 GPa</td>
</tr>
<tr>
<td>Compressive Yield Strength</td>
<td>3.59 MPa</td>
</tr>
<tr>
<td>Shear Strength</td>
<td>7.45 MPa</td>
</tr>
<tr>
<td>Work to Elastic Limit</td>
<td>0.00414 J/cm³</td>
</tr>
<tr>
<td>Work to Maximum Load</td>
<td>0.0731 J/cm³</td>
</tr>
<tr>
<td>Cleavage</td>
<td>52.0 kN/m</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>4.0 %</td>
</tr>
</tbody>
</table>

MatWeb's searchable database of material properties
Models based on stand and tree characteristics?
Variation in properties within and between trees

- Suppressed:
  - Less foliage
  - Narrow annual rings
  - Smaller knots
  - Higher density
  - Better mechanical properties

- Dominant:
  - More foliage
  - Wider rings
  - Larger knots
  - Lower density
  - Poorer mechanical properties

Olav Albert Høibø, NMBU.no
Wood density in trees (Norway spruce)

Relative Diam. (BH)

Site index G 11

Site index G 17

Site index G 24

Relative height

Olav Albert Høibø, NMBU.no
Models based on growth patterns?
Models based on wood tissue types?
Scots pine stumps for gasification

Prediction of heartwood diameter (amount of extractives)

Models based on type of tree fraction?
Direct seeding of lodgepole pine

Assortments/tree fractions, lodgepole pine ca 30 yrs

950 kg of stem extractives/ha
990 kg of bark
660 kg of branch
370 kg of needle
3.0 kg needle wax/ha
Models based on silviculture?
Per cent long (≥ 2.5 mm) fibres, age 50-80 yrs

Volume of fibre in different length classes

Dense/Sparse regime

Sparse regime

Long fibres
Models based on price of electric power?
Models based on possible end use?
Timber

Pulp

Fuel

Wood

Solid

Wood

Products

Fiber

Products

Bioenergy

Terpenes

Ketones

Waxes

Cosanols

Phytosterols

Lignocell.

Terpenes

Ketones

Fats

Terpenes

Ketones

Waxes

Fats

Lignocell.

Resins

Fats

Aromatics

Resins

Fats

Assortments for biomass harvest?

Needles

Branches

Bark

Stem

Wood

Cones

Models linked to harvester through computer vision?
Many sensors available for machine vision...

- Bend sensors
- Light sensors
- Temperature sensors
- Potentiometers
- Laser rangefinders
- Cameras
- Touch sensors
- Tilt sensors
- Encoders
Tree Detection

Rapid image display techniques for estimating biomass of young trees

Shafiq ur Réhman, Umeå University
Detection of clear-cut obstacles using TOF-camera

Water maps
Detection concepts: soil/terrain & trees

Semiautonomous "shared-control" of forestry machines

Models to select trees
- Biomaterials in trees

Water quality, terrain & vehicles

- Terrain models
- "Path planning"
- Models for bearing capacity
From tree assortments to an engineering biomaterial in industry

Needs:

- Characterisation of "the feed-stock biomaterial" in several steps of the different value chains
- Cost-effective techniques for in-line measurements of material properties
- Techniques to communicate properties in value chains
- Techniques to extract one material and then continue to extract...
Thanks!

”Commercial reality or myth?”

I THOUGHT IT WAS TOMORROW?