Three steps to improved TMP operating efficiency

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Abstract
This paper introduces a concept which reduces the challenges associated with the thermo-mechanical pulping (TMP) optimization. It is based on a new family of fiber analyzers used in conjunction with computer models which has been developed based on a large amount of empirical data.

The mechanical pulping process continues to be pressured by reduced revenues from sales in combination with increasing production cost. This is particularly true in NA and Scandinavia, where the cost of electrical energy has increased sharply over the last couple of years. As a consequence, mill optimizations, and process control is becoming increasingly important, since it can offer significant performance improvement without large changes to the plant and operating conditions. One challenge is the cost associated with the optimization and control implementation. There are literally hundreds of variables to be considered as a function of time, and using traditional methods vast amounts of pulp samples would need to be collected and analyzed before a robust control strategy could be implemented.

The fiber diagnostic module is a portable fiber analyzer which allows us to map out the mill very efficiently in terms of fiber quality development throughout the process. Quality versus cost relationships are established at the mill using design of experiments for all key machinery. The fundamental fiber quality data collected are linked to a computer model, which calculates the pulp freeness, density and strength parameters and reviews the operating costs for the mill. Set-points and operating target windows are then established for the operation. Finally in-line analyzers are installed in key positions in the mill to provide real time quality and cost data at high sampling frequencies. This concept ensures that the optimization process conducted becomes “a live document”, rather than just a snap shot picture.

Forgacs[1] showed already in the 1960’s, that the physical properties of mechanical pulps, could to a large extent be characterized by two parameters, specific surface area, and fiber length of the +48 fiber fraction. In the 1980’s Strand [2] introduced a similar approach using multivariate analysis. The concept of on-line modeling based on mechanical engineering analysis was first introduced at the IMPC 2005 conference in Oslo by Johansson [3]. Since then it has been possible to reduce the complexity of both hardware and software to the point where a very simple and robust system is in place which predicts hand sheet properties based on the geometry of thousands of fibers. In this paper, the results from several mill studies utilizing this measurement device together with simple optimization techniques are presented.

The three simple steps of the optimization process will be discussed, and examples of each step will be given. The paper is concluded with a discussion on typical overall mill improvements.

Background
The main advantages of refiner based processes over other processes are related to yield, relatively simple implementation, and until recently, low production cost. Today however, the advantage is being threatened by the increasing cost of electrical energy. Since the introduction of the TMP process some thirty years ago, the cost of electrical energy has more than doubled in many regions of the world. This is particularly true here in North America.

Several significant improvements have been implemented over the years, such as pressurized heat recovery, large and more efficient refiner systems, advanced control systems and advanced refiner segment designs. Today, many mills are being challenged by cost-saving initiatives. Engineering and technical staff has been reduced in some cases below long term sustainable levels, and in many cases, the mill technical department and on-site laboratory have become things of the past. As a consequence, relatively few optimization studies are conducted today, and many mills are operating below optimal conditions.
The InovoCell fiber analyzer is a new simple device which is potentially capable of eliminating the need for time-consuming and costly pulp and hand sheet preparation and testing. This optical device is based on the same principals first introduced by Dr Jan Hill some thirty years ago, in conjunction with modern computational tools.

![Figure 1. First on-line analyzer patent application, 1974, Jan Hill.](image1)

Figure 2. InovoCell diagnostic fiber tester.

A copy of Hill’s patent for the detailed measurement of shives and their size distribution using an optical analyzer [4] is shown in Figure 1. Figure 2 shows the new Inovocell diagnostic fiber analyzer which can be used for measuring the important geometric parameters associated with fibers in aqueous suspension. In conjunction with some sophisticated software, these parameters can quickly be converted into freeness measurements and physical property profiles of the particular pulp in question without the need for tedious and time-consuming hand sheet preparation, conditioning and testing.

In a TMP mill, electrical energy is used to drive refiners, pumps, agitators, screens, blowers and fans. However, more than eighty percent of the consumed electrical energy is applied in the refiners, and it is natural to focus on the refiner systems in order to reduce operating costs. However, the same techniques are applicable to most sub systems or equipment in the mill. In order to illustrate the opportunity, we have defined a refining efficiency index as the tensile index per unit of applied specific energy as indicated in the following expression:

\[ \eta = \frac{\text{Tensile Index}}{\text{Specific Energy}} \]  

(1)

Table 1 lists the refining efficiency index for fourteen different mills in North America and Scandinavia [5], and it is evident from the table that these mills cover a significant range in terms of refining efficiency.
There are a number of factors which can explain these observed differences:

- Differences between wood species with stiff, thick-walled summerwood fibers behaving very differently from flexible thin-walled springwood fibers.
- Different types of refiners (single disc, twin flow, counter-rotating double disc and CD refiners).
- Differences in process conditions and auxiliary machinery
- Seasonal effects with respect to raw material
- Process measurement errors
- Different laboratory test procedures

It is well known that the raw material used in different parts of the world exhibits vastly different geometrical properties, and will therefore produce very different pulps as outlined in Figure 3.

<table>
<thead>
<tr>
<th>Wood Species, Balsam Fir</th>
<th>Refiner Type</th>
<th>Freeness ml</th>
<th>Tensile Index 1000g</th>
<th>Specific Energy kWh/kg</th>
<th>Energy Efficiency kWh/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Spruce, Jack Pine</td>
<td>Hymac Single Disc</td>
<td>150</td>
<td>38.1</td>
<td>2.330</td>
<td>16.6</td>
</tr>
<tr>
<td>Black Spruce, Jack Pine</td>
<td>RGP CD76</td>
<td>162</td>
<td>37.2</td>
<td>1.698</td>
<td>21.9</td>
</tr>
<tr>
<td>Interior Spruce Pine Fir</td>
<td>Anidzts Twin 60</td>
<td>180</td>
<td>36</td>
<td>2.014</td>
<td>17.9</td>
</tr>
<tr>
<td>Interior Spruce Pine Fir</td>
<td>Bauer Double Disc</td>
<td>103</td>
<td>41</td>
<td>2.239</td>
<td>18.3</td>
</tr>
<tr>
<td>Interior Spruce Pine Fir</td>
<td>Bauer Double Disc</td>
<td>122</td>
<td>37</td>
<td>1.944</td>
<td>15.0</td>
</tr>
<tr>
<td>Interior Spruce Pine Fir</td>
<td>Bauer Double Disc</td>
<td>125</td>
<td>36</td>
<td>1.886</td>
<td>15.1</td>
</tr>
<tr>
<td>Interior Spruce Pine Fir</td>
<td>RGP CD76</td>
<td>173</td>
<td>30</td>
<td>1.910</td>
<td>15.7</td>
</tr>
<tr>
<td>Interior Spruce Pine Fir</td>
<td>RGP CD76</td>
<td>150</td>
<td>36.7</td>
<td>2.360</td>
<td>15.5</td>
</tr>
<tr>
<td>Interior Spruce Pine Fir</td>
<td>RGP CD76</td>
<td>160</td>
<td>36.2</td>
<td>2.360</td>
<td>14.9</td>
</tr>
<tr>
<td>Lodgepole Pine</td>
<td>RGP CD76</td>
<td>128</td>
<td>30</td>
<td>2.150</td>
<td>17.7</td>
</tr>
<tr>
<td>Lodgepole Pine</td>
<td>RGP CD76</td>
<td>236</td>
<td>25.2</td>
<td>2.166</td>
<td>11.5</td>
</tr>
<tr>
<td>Lodgepole Pine</td>
<td>RGP CD76</td>
<td>240</td>
<td>30.4</td>
<td>2.185</td>
<td>13.9</td>
</tr>
<tr>
<td>Lodgepole Pine</td>
<td>RGP CD76</td>
<td>222</td>
<td>24.8</td>
<td>1.956</td>
<td>12.4</td>
</tr>
<tr>
<td>Scandinavian Spruce</td>
<td>Metsa-EE</td>
<td>157</td>
<td>38</td>
<td>1.804</td>
<td>21.1</td>
</tr>
<tr>
<td>SPF</td>
<td>RGP CD79</td>
<td>120</td>
<td>35.2</td>
<td>2.091</td>
<td>18.7</td>
</tr>
<tr>
<td>SPF</td>
<td>RGP CD79</td>
<td>133</td>
<td>46.5</td>
<td>2.083</td>
<td>19.4</td>
</tr>
<tr>
<td>White Spruce, Lodgepole Pine</td>
<td>RGP CD70</td>
<td>173</td>
<td>35.4</td>
<td>2.121</td>
<td>16.7</td>
</tr>
<tr>
<td>White Spruce, Lodgepole Pine</td>
<td>RGP CD70</td>
<td>189</td>
<td>32.5</td>
<td>2.187</td>
<td>14.9</td>
</tr>
<tr>
<td>White Spruce, Lodgepole Pine</td>
<td>RGP CD70</td>
<td>208</td>
<td>33</td>
<td>1.762</td>
<td>18.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wood Species, Balsam Fir</th>
<th>Refiner Type</th>
<th>Freeness ml</th>
<th>Tensile Index 1000g</th>
<th>Specific Energy kWh/kg</th>
<th>Energy Efficiency kWh/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>152</td>
<td>34.7</td>
<td>2.089</td>
<td>16.7</td>
<td>51</td>
</tr>
<tr>
<td>Max</td>
<td>240</td>
<td>41.0</td>
<td>2.568</td>
<td>21.9</td>
<td>150</td>
</tr>
<tr>
<td>Min</td>
<td>155</td>
<td>24.8</td>
<td>1.888</td>
<td>11.6</td>
<td>43</td>
</tr>
<tr>
<td>Std</td>
<td>30</td>
<td>4.2</td>
<td>5.194</td>
<td>2.6</td>
<td>26</td>
</tr>
</tbody>
</table>
However, in order to establish the relative importance of refiner type, a series of refiner energy curves were generated and the pulps, all of which were based on Norwegian spruce as the source of raw material, were analysed with the Inovocell diagnostic unit. In addition, in order to investigate the effect of operating parameters on the refining efficiency, a detailed optimization study was then performed on a single disc refiner, using the same equipment and techniques.

**Experimental**

**Step 1: Is there an opportunity?**

The first objective is to establish if any opportunity exists for improvement, and if so how big this opportunity is. This step can be on a corporate level, mill level, and down to the refining equipment level.

As an example, a series of different refiner types operating in Sweden was investigated. All refiners are operating at 1500 rpm and in all cases the raw material is Norwegian Spruce. In each case, different energy levels were applied using disc-gap adjustment for refiners controlled by displacement and hydraulic load for refiners controlled by force. Pulps produced by different refiner types operating under different conditions were compared using the InovoCell fiber transmitter, and process data were collected from the respective DCS systems.

**General**

Two sets of calibration curves were generated using a single stage counter-rotating refiner and a two stage single disc refiner system. The pulps were analyzed in two separate laboratories. Figure 4 shows the freeness and tensile index plotted as a function of applied specific refining energy. It is evident that the computed values of freeness and tensile index are in good agreement with the laboratory measured data.
Figure 4  Freeness and tensile index as functions of specific refining energy

Refiner Type Trials

Figures 5 and 6 show the InovoCell calculated freeness and tensile strength values plotted against the specific energy consumption in refining. These graphs show good differentiation between refiner types and production rates, with the double disc refiners providing more favorable freeness versus specific energy and tensile index versus specific energy relationships than the smaller and lower production rate single disc refiners.

Figure 5  Relationship between computed freeness and specific energy
Due to the competitive situation between suppliers of refiners and refiner segments, we have not been able to compare the refining intensity in terms of edge load or refiner bar area loads. We can, however, compare the operations in terms of the power applied per unit refining area, assuming the power is dissipated much like a disc-break system. As outlined in equations 2 - 6:

The dissipated power at a given radius can be computed as the force multiplied by velocity in the tangential direction at that radius

\[ P = F \cdot v \quad (2) \]

\[ F(r) = \mu(r) \cdot N(r) \cdot 2\pi r \quad (3) \]

\[ v = \omega \times r \quad (4) \]

then the power applied over the refiner is given by:

\[ P = \int_{r_i}^{r_f} \mu(r)N(r) \cdot 2\pi r \cdot \omega \times r \, dr \quad (5) \]

\[ P = 2\int_{r_i}^{r_f} \mu(r)N(r) \cdot \omega \cdot \pi r^2 \, dr \quad (6) \]

Figures 7 and 8 show the calculated freeness and tensile strength values plotted against the refining intensity defined as kW/m². Once again, the plots show clear differentiation between single disc and double disc refiners.
Figure 7  Freeness as a function of refining intensity

Figure 8  Tensile index as a function of refining intensity

Figure 9 shows the so-called tensile efficiency index mentioned earlier plotted against the computed freeness values. It is evident that smaller diameter single gap refiners exhibit a lower tensile strength efficiency than either the twin flow, CD, or the double disc refiners.
Step 2: Establish optimal operating conditions

Process optimization

It is evident from figures 5 - 9 that the type of refiner equipment influences the amount of energy consumed in attaining a given level of drainage and strength. Of the refiner group investigated, the counter-rotating refiner is the most efficient, and it is clear that the refining intensity (measured as kW/unit area) is the highest for the counter-rotating refiners. The results also point toward improved efficiency with increased production rate over a given refiner. These results are in line with the studies presented by Strand at the IMPC held in Oslo in 1993 [6] as indicated in Figure 10.

The process can be optimized for a given set of equipment using the InovoCell diagnostic analyzer for the quality analysis coupled with process data from the mill DCS system. Because of the lower effort required to analyze the pulps, it is no longer necessary to limit the number of variables involved in the study.

In the following example, the effect of disc-gap and refining consistency of the primary refiner in a two stage system on pulp quality and refining efficiency is mapped out.
Trial plan and Response Map

The overwhelming advantage of a designed experiment is that the system under evaluation can be manipulated. With design of experiments (DOE), fewer data points are generated than by using passive instrumentation, but the quality of the information obtained will be higher. In this example, the two variables, refining gap and refining consistency are investigated at three different levels. Using a full factorial design with two repeat points, the trial required less than 12 samples. The total time required for the trial including the analysis was less than 8 hours. Figure 11 shows graphs of the raw data from the primary refiner trial.

![Figure 11](image1.png)

Figure 11  Raw data for Inovocell tensile index as a function of applied specific energy and computed freeness

Using a commercial software program MatLab [7], a response map can easily be generated from the data obtained from the DCS and InovoCell systems. Figure 12 is a typical refiner response map showing how the primary gap and consistency affect the energy consumption, freeness, and primary and secondary tensile indices. The red dashed lines represent 90% confidence limits.

![Figure 12](image2.png)

Figure 12  Primary refiner response map (Matlab)
Using this tool, it is possible to investigate interactively the effect of changes in refining gap and consistency plotted on the X axis on important response variables plotted on the Y axis. Table 2 lists the refiner line response, with the refining consistency and applied energy in second stage refining maintained constant during the trial.

Table 2. Refiner line response to primary gap and consistency

<table>
<thead>
<tr>
<th>Delta Gap</th>
<th>Cons</th>
<th>Sec</th>
<th>CSF</th>
<th>CTS, Index</th>
<th>S Tens, Index</th>
<th>Eff. Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>%</td>
<td>kWh/t</td>
<td>mI</td>
<td>Nm/g</td>
<td>dN/m</td>
<td>kN/m/kWh</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
<td>1673</td>
<td>204</td>
<td>12.9</td>
<td>27.89</td>
<td>16.7</td>
</tr>
<tr>
<td>0</td>
<td>47</td>
<td>1778</td>
<td>175</td>
<td>14.1</td>
<td>31.6</td>
<td>17.8</td>
</tr>
<tr>
<td>0</td>
<td>55</td>
<td>1868</td>
<td>172</td>
<td>13.6</td>
<td>34.5</td>
<td>18.5</td>
</tr>
<tr>
<td>-0.17</td>
<td>40</td>
<td>1878</td>
<td>154</td>
<td>16.9</td>
<td>31.7</td>
<td>16.9</td>
</tr>
<tr>
<td>-0.17</td>
<td>47</td>
<td>1899</td>
<td>138</td>
<td>17.1</td>
<td>34.6</td>
<td>18.2</td>
</tr>
<tr>
<td>-0.17</td>
<td>55</td>
<td>1902</td>
<td>148</td>
<td>15.6</td>
<td>36.3</td>
<td>19.2</td>
</tr>
<tr>
<td>-0.35</td>
<td>40</td>
<td>2030</td>
<td>121</td>
<td>19.2</td>
<td>36.8</td>
<td>18.1</td>
</tr>
<tr>
<td>-0.35</td>
<td>47</td>
<td>1980</td>
<td>117</td>
<td>18.3</td>
<td>38.7</td>
<td>19.5</td>
</tr>
<tr>
<td>-0.35</td>
<td>55</td>
<td>1911</td>
<td>137</td>
<td>17.0</td>
<td>39.5</td>
<td>20.7</td>
</tr>
</tbody>
</table>

Optimal conditions

Using the interactive computer model, the optimal refining operating conditions can be established as shown in Figure 13. In this case, the tensile index increases with increased primary consistency, while the specific energy consumption goes through an inflection point with increased consistency. Finally the refining efficiency is plotted in Figure 14.

Figure 13. Specific energy requirement and tensile strength as a function of primary refining consistency for three different disc gaps.
Step 3: Keep it there

Sustainable improvement

With the opportunities established from optimal operating conditions, the challenge is to keep the mill operating continuously under the optimal conditions. Over the years many advanced control systems such as the Metso-PacSim AQS [8] and less advanced systems such as the Smart Plates of J&L [9] have been installed with significant improvements as a result. The installation and service costs, however, are often prohibitive for small or medium size mills. A large portion of this cost can be attributed to the pulp analyzers (both machine and installation) which until now have been for the most part highly advanced electromechanical devices, requiring a complex network of sample lines and operating logic to function properly. A typical fiber analyzer contains many different components such as pumps, control valves, drives, consistency meters, chambers and electronics in addition to the actual measurement cell. As a consequence of many components and complex interactions, on-going maintenance and continual checking and calibration of the equipment is essential to the success of the project.

The InovoCell fiber transmitter offers a different approach to the traditional batch-mode fiber analyzers. Instead of sampling through a sample valve and then feeding the sample to a central unit, the InovoCell unit is placed directly in the pipe transporting the pulp at a consistency in the range of 0 – 9 % as indicated in Figure 15.

Utilizing the dynamic pressure in the pipe significantly reduces the complexity and parts required for the measuring cell. The significant reduction of the number of components required, which are now limited to a camera, a suitable light source and a stepping motor, has now made it possible to reduce both the installation and service cost significantly.

A cross-section of the fiber transmitter is shown in Figure 16. The dynamic pressure drives the pulp mixture through the sensor head, where dilution water is being added (A). The suspension is diluted to less than 1g/l (B) before being forced in front of the CCD camera (C, D). At this stage, pictures are taken through the glass windows of the cell, the depth of which can be adjusted for different applications (C). The camera is used to monitor the number of fibers in each frame. The light source (E) creates a contrast gray image, and this is converted to a binary image using standard image analysis libraries. During the image acquisition and control, the fiber morphological data are stored for subsequent engineering analysis during the post processing. Several different convergence criteria can be set up, but typically the solution can be considered to have converged when the change in fiber length has reached a threshold value of 1-2 percent.
The required computations and analysis are made on a built-in PC in the CCD camera. In addition, the built-in PC controls the flow through the cell, as well as communication, alarms, and diagnostics. The fibers are fed back into the pipe due to the pressure drop across the cell (f). The results are fed to any computer on a standard TCP/IP network. This network can be hard-wired or wireless depending on the preferred installation.

Over the years, the quality of the fiber images has improved significantly, primarily due to the increased resolution of the digital camera. Today, an image with a resolution of 5-10 um is quite common. The intensity of the gray-level images is used to approximate the cell wall thickness and for computing the amount of material present in each fiber. Figure 17 is a gray level image with the contours representing the gray-level intensity.
Performance Reports

In its simplest form, the InovoCell quality transmitter can be used to automatically generate performance reports, based on measured pulp quality, process conditions and cost. These reports can be web-based or integrated to a customer-specific system. Figure 18 is an example of a Web application which (with the correct security levels) can be accessed from most locations in the world over the internet. With a tool like this, corporations can effectively manage and drive out costs on a world-wide basis, for a minimal investment.

Operator guidance

Operator guidance in different forms is a proven concept for improving plant efficiency. For example, Olof and Rita Ferritsius [10] introduced the use of $F_1$ and $F_2$ factors with data displayed on so-called “worm charts” as shown in Figure 19. Today, these charts are used in many Stora Enso mills for quality assurance purposes. The Inovocell pulp quality transmitter can easily be configured or integrated into systems for operator guidance purposes.

Control system

The camera actions, data analysis, controls etc. are easily configurable through the use of an “open source” scripting language, and can therefore be integrated into any control system, or even perform basic controls with the built-in PC. Mill-wide control systems are offered by many manufacturers, and the InovoCell transmitter can be integrated to most systems for feed-back on resulting fiber quality.
Concluding Remarks

There is nothing new associated with scanning a pulp suspension with the aid of a high resolution digital camera to generate the morphological properties associated with a population of pulp fibers. What is new and exciting, at least to us, is the ability to transform this information almost in real time into a set of parameters which define the physical properties of a pulp that will ultimately contribute to the physical properties of paper without the long delay normally involved in acquiring a pulp sample, testing it, producing a set of pulp hand sheets, drying and conditioning the sheets and finally testing them. The process outlined in this paper removes all of the tedium from the analysis and immediately provides the plant manager with the information required to do a more effective job in running the operation in a cost-effective manner.

In addition, the number of components of the measuring device has been reduced significantly, greatly reducing the need for costly maintenance and service.

Utilizing the InovoCell fiber quality transmitter in conjunction with “canned” analysis software packages and techniques, significant improvements can be achieved by optimizing the existing equipment. In our example, a ten to fifteen percent refiner efficiency opportunity was shown for a two stage single disc refiner system.

Acknowledgement

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References