CONTROLLING TMP REFINER LINES USING PRE-SPECIFIED OPERATING WINDOWS

Karin Eriksson¹, Anders Karlström¹, Lars Ledung²

¹Chalmers Industrial Technology, Chalmers Science Park, SE-412 96 Göteborg, SWEDEN
²ABB AB, SE-721 59 Västerås, SWEDEN

ABSTRACT

This paper shows how the introduction of a new refiner control system can accomplish stabilization of the process conditions as well as constitute a tool for better energy efficiency. The control system is based on a cascade structure where the refining zone temperature is controlled in the inner loop whereas the outer loop handles the pulp quality. The hydraulic pressure controls and stabilizes the maximum value of the temperature profile, \( T_{\text{max}} \), and as a result, the variations in motor load and pulp quality are reduced.

The information obtained from temperature profile measurements is by no means equivalent to that given from the refiner motor load. It is shown that control of the refining zone temperature stabilizes the refining zone conditions which results in a stabilization of the refiner motor load. It is noteworthy that a control strategy that primarily aims at stabilization of the refiner motor load will not manage to stabilize the process conditions inside the refining zone as a result of, for example, fiber pad fluctuations.

From studies of operating windows, i.e. a working space spanned by the operating conditions in the primary and the secondary refiner, a significant potential for increased energy efficiency is identified. The results show that the energy consumption in the refiners can be reduced by 6-12%, which for the mill studied corresponds to 30-60 GWh/year. These savings can be obtained within the operating windows for different pulp quality variables that are considered acceptable today.

From an evaluation perspective it is also shown that, an operating window approach will give a better picture of the process performance than can a traditional approach using statistical measurements. This is pinpointed by the reduction in standard deviations which was found fluctuating between 30-60% for CSF, MFL and shives, when comparing different large sets of data. Clearly, special care is needed when applying statistical tools on data from a highly-interacting multi-input-multi-output process like this.

INTRODUCTION

A competitive power price has been a distinctive trait in many countries during the last decades. Especially, this has been an important factor for the energy intensive pulp and paper industry. Lately the situation has changed and, in order to stay on the market, it has been necessary for modern mills to focus on reduction of operating costs. Significant improvements have been made and many projects, both in industry and in academia, aim at improved energy efficiency of pulp- and paper-making processes. Still, achieving a reduction in for example electricity consumption remains a difficult task where several problems have to be addressed.

The process computer systems of today give easy access to data from hundreds of sensors, but such information can in most cases not be used to acquire knowledge about inherent process conditions. The reason for this is that a majority of the sensors is placed outside the process equipments. This is the case in most TMP and CTMP plants. To reach a maximized production with good pulp quality and acceptable energy consumption, it is sometimes essential to understand the conditions inside the actual refining zone.

Minimization of deviations from target quality can also be considered essential, but herein lies an inherent difficulty as there exists many ways to approach the “right” pulp quality. In addition, the economic value of reduced quality variations is difficult to estimate due to the complexity of the process. As a result, it is not straightforward to specify neither desired product properties nor desired process conditions. Clearly, more efforts are needed in this area.

Earlier research has shown that information about temperature profiles, directly measured in the refining zones, can play a vital role in describing the process conditions (see e.g. [1-10]). Such measurements capture fast dynamics related to the energy balance which is one piece to understand the cause of pulp quality variations in a short time scale. Even though other technologies exist for measurement of variables directly in the refining zone, temperature measurements have proven to be robust enough for such extreme process environments. For refining processes, it is an understatement that robustness of sensors is one of the keys to a successful implementation of reliable control systems. So far, this technology has been used primarily to develop mathematical models for refining processes and, in addition, to form a basis for new soft sensor technologies [7-11].

Although refining zone temperature measurements have been much considered, few projects have installed sensors in both primary and secondary refiner for control purposes. However, the availability of such measurements enables a rather extensive mapping of the process conditions by, for example, an operating window approach like presented in this paper. The use of such analysis methods are uncommon for TMP refining processes, while in the oil industry it is close to common practice.

For a long time, it has been known that specific energy alone is insufficient to completely characterize the refining process (see e.g. Hill et al. [12], Johansson et al. [13], Dahlqvist and Ferrari [14]). This statement has also an impact on the possibility to specify a well-controlled operating window for pulp quality. The main reason is that the specific energy is affected, not only by...
the variations in production rate, but also by variations in amount of dilution water fed to the machines, different plate gaps and complex process related phenomena like, for example, changes in the refining zone fiber distribution.

To meet pulp quality demands, new robust control strategies for refiners must be developed where the operators face the complexity of the refining processes from a new perspective, compared with the view offered by most process computers of today. The key questions of this paper are how a small operating window can be targeted, and how such a narrow region can be related to plant economy, if applying refiner control to stay within that region.

The first section of the paper comprises the fundamentals regarding process description and current control approaches. Moreover, it discusses terms like operating window and test procedure in combination with economic considerations. The idea is to introduce a balanced picture where several aspects of finding a “good enough quality” are considered. The next section covers the results obtained when running a full-scale production line in automatic control. Finally, conclusions are drawn given a focus on the use of temperature sensor arrays inside the refining zones in full-scale TMP/CTMP production lines.

**FUNDAMENTALS**

In general, traditional process control systems for refiners do not comprise any spatial information from the refining zone. In this paper, information of refining zone temperature profiles is essential for a new cascade control concept called TCtrl. The process data that is used for analysis has been obtained from a full-scale production line with two serially linked refiners.

Traditionally monitored process variables like production rate, dilution water flows, hydraulic pressures and motor loads are measured for both refiners. Canadian Standard Freeness (CSF), mean fiber length (MFL), fiber fractions and shives are measured after the refiner line. In addition, the temperature variations due to unstable fluctuations at stationary operation are monitored.

In this paper, information of refining zone temperature profiles is essential for a new cascade control concept called TCtrl. The process data that is used for analysis has been obtained from a full-scale production line with two serially linked refiners.

In general, traditional process control systems for refiners do not comprise any spatial information from the refining zone. In this paper, information of refining zone temperature profiles is essential for a new cascade control concept called TCtrl. The process data that is used for analysis has been obtained from a full-scale production line with two serially linked refiners.

Traditionally monitored process variables like production rate, dilution water flows, hydraulic pressures and motor loads are measured for both refiners. Canadian Standard Freeness (CSF), mean fiber length (MFL), fiber fractions and shives are measured after the refiner line. In addition, the temperature profiles were measured each second in both refiners, using an array of eight sensors spatially located in the refining zones. This makes it possible to span a comprehensive operating window from different production perspectives. The types of process variations that the control system, in general, aims at are indicated in Figure 1.

Figure 1: Different types of process variations in the operation of a TMP refiner. In italics, time scale for refining zone temperature control concepts.

**Control concept**

As described by Eriksson and Karlström [10], the obtained temperature profile, see Figure 2, is a consequence of the friction between the plates, the chips/pulp and the added dilution water when reducing the plate gap. The steam built up inside the refining zone is evacuated both forward (towards the periphery of the segments) and backwards (towards the chip inlet). There is a stagnation point at some radius in between where the maximum temperature \( T_{\text{max}} \) at the radial position \( r_{\text{max}} \) is found.

Instead of using the entire temperature profile, the TCtrl concept only uses the maximum temperature. The position for \( T_{\text{max}} \) can vary over time and is indeed dependent on the segment design and taper. This choice is based on the physical process behavior illustrated in Figure 3. This figure shows low-frequency gains \( K_{ij} \) estimated using data from a full-scale twin refiner in primary position. It can be seen that temperature sensors \( T_1 \) and \( T_2 \) as process output would give a small gain from the dilution water feed rate, while the other temperature sensors lead to larger gains. Moreover, the effect on consistency is, as expected, small when changing the hydraulic pressure and the production rate, but changes in the production rate can of course affect the outlet consistency considerably, for example, if the input consistency differs a lot when changing feed stocks. Altogether, this identifies the hydraulic pressure as a good input candidate for any control concepts.

**Figure 2:** A typical temperature profile from a primary refiner where a sensor array is placed between two segments.

**Figure 3:** Low-frequency gains from a primary refiner for different elements in a 10x3- system.
Similar information can be obtained from a twin refiner in secondary position, see Figure 4. It is natural the gains can differ related to changes in process conditions such as plate designs.

![Diagram of Twin Refiner](image)

**Figure 4:** Low-frequency gains from a secondary refiner for different elements in a 10x3-j- system.

Selecting a temperature sensor such as \( T_S \) or \( T_P \) as the controlled output will produce a small gain from the dilution water feed rate for this refiner. The consistency is affected in the same way as in the case of the primary refiner when changing the hydraulic pressure and the production rate.

In all cases studied so far the shift in the low-frequency gain, when changing the dilution water feed rate, coincide with the position where the maximum temperature \( T_{\text{max}} \) is located [15]. All this, is clearly valuable when attempting to introduce natural decoupled systems in order to minimize the undesired interaction between input and output elements. This is easiest explained by studying the system

\[
Y = \frac{T_{\text{max}}}{C} = G U = \begin{bmatrix} g_{11} & 0 \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} P_{\text{hydr}} \\ F_D \end{bmatrix}
\]

where the hydraulic pressure \( P_{\text{hydr}} \) and the dilution water flow \( F_D \) are considered as elements in the input vector \( U \) and the variables \( T_{\text{max}} \) and \( C \) belongs to the output vector \( Y \)[16,17].

Variations in the production rate will also affect the temperatures and consistency, but in most control concepts this is handled as noise as the production is assumed to be kept relatively constant. In the inner control loop of the cascade concept called \( T_Ctrl \), see Figure 5 and Table 1, the maximum temperature is used to control the process in one SISO-system for each refiner. Since the concept of natural decoupling is equivalent to an introduction of zeros in the anti-diagonal elements of \( G \), it is obvious that the consistency control loop can be considered separately. Therefore, not much focus will be put on the consistency control loop in this paper.

**Operating windows**

For a refining process, an operating window can be specified in many ways. One approach is to describe the motor load versus the plate gap and, considering this relation, it is clear that a reduction in plate gap will result in an increased motor load to a certain point where a plate clash occurs. This was originally discussed by Dumont and Åström [18], and DiRuscio [19], while the first simulated results based on a rigorous entropy model, was presented by Eriksson and Karlström [11]. For control purposes, such an operating window has a draw-back as it is hard to confirm the true plate gap. Moreover, the variables plate gap and motor load cannot give information about the actual process conditions which are vital when considering process control applications.

Another way to describe the operating window is to illustrate how some selected pulp quality variables relate to each other during continuous process operation. An example is given in Figure 6 where \( T_Ctrl \) is in manual mode (OFF).

In Figure 6, like in every figures showing different operating windows, the value zero on an axis represents the variable mean value for all measurements depicted in that figure. Thus, the numerical values indicate deviation from mean value in the unity given by the axis label.

Normally it is difficult to follow a complete production line only by analyzing the types of operating windows described above and therefore, more rigorous tools must be developed. One approach is to consider operating windows spanned by the operation conditions in the primary and the secondary refiner. This is exemplified in Figure 7 and 8 where the motor loads and the maximum temperature in the primary and secondary refiners can form operating windows. From these operating windows new interesting information can be extracted like the raw material impact on the final pulp quality, see Figure 6.

![Diagram of Cascade Control](image)

**Figure 5:** Schematic drawing of the cascade control concept called \( T_Ctrl \) used for two serially linked Twin-refiners.

![Table 1](image)

**Table 1:** Description of items referred to in Figure 5.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r )</td>
<td>Reference signal for outer loop, quality variable</td>
</tr>
<tr>
<td>( y )</td>
<td>Output signal from outer loop, measured quality variable</td>
</tr>
<tr>
<td>( T_{\text{maxP}} )</td>
<td>Maximum temperature in primary refiner (P)</td>
</tr>
<tr>
<td>( T_{\text{maxS}} )</td>
<td>Maximum temperature in secondary refiner (S)</td>
</tr>
<tr>
<td>( b )</td>
<td>Hydraulic pressures</td>
</tr>
<tr>
<td>( u )</td>
<td>Temperature change to adjust control error</td>
</tr>
<tr>
<td>( P )</td>
<td>Controllers for the outer loop (pulp quality control)</td>
</tr>
<tr>
<td>( Q )</td>
<td>Controllers for the inner loop (temperature control)</td>
</tr>
<tr>
<td>( g )</td>
<td>Distribution of the estimated temperature change to each refiner</td>
</tr>
</tbody>
</table>

Control Systems 2010 3
Quality A (marked as black dots in Figure 6) represents a certain mix of saw mill chips and virgin feed stock. Quality B (marked as grey circles) represents a mix which has a lower portion of saw mill chips. Moreover, we can also conclude that all measurements in Figure 6 together represent an operating window with acceptable pulp quality as it is obtained during normal operation with no complaints from the customers. These statements will be discussed further below.

If different types of operating windows are considered simultaneously, even more interesting information can be obtained. In Figure 7 it can be seen that the motor load is spread over a relatively large area in the operating window. This indicates that there exist a number of ways to end up with an acceptable pulp quality. Turning to Figure 8, where the maximum temperatures in the refining zones are plotted against each other, it is clear that the temperature and the motor load shown in Figure 7 are not following each other. The reasons have been penetrated by Eriksson and Karlström [10] where it was concluded that the specific energy (or the motor load) is an integrated measure and by that it has obvious limitations compared to measurements providing information about the refining zone conditions.

Figure 6: Operating windows of pulp quality in terms of Canadian standard freeness, CSF, and mean fiber length, MFL, when running the process only by using the consistency control loop. Note that the value zero on both axes represents the variable mean value for all measurements shown in the figure.

In the pulp and paper industry, operating windows are commonly discussed using pulp quality as a function of specific energy consumption. However, given the limitations of the specific energy [10, 12-14] it is obvious that new approaches could be considered in order to broaden the perspective and to clarify hidden potentials for control improvements.

Figure 7: Operating windows of motor loads for two serially linked refiners when only using the consistency control loop.

Figure 8: Operating windows of maximum temperature for two serially linked refiners when only using the consistency control loop.

The test procedure used in the evaluation was designed to represent different refiner operation, i.e. $TCtrl$ in manual mode (OFF) and in automatic mode (ON). Figure 9 exemplifies the test period for evaluation of the temperature control, i.e. the inner loop of $TCtrl$.

Test procedure

The test procedure used in the evaluation was designed to represent different refiner operation, i.e. $TCtrl$ in manual mode (OFF) and in automatic mode (ON). Figure 9 exemplifies the test period for evaluation of the temperature control, i.e. the inner loop of $TCtrl$. 

Figure 9: Test period: Data sets 1,2,3,...,11 represents $TCtrl$ ON and R1,R2,...,R6 represents $TCtrl$ OFF. The line indicates when $TCtrl$ is ON or OFF.
To assure a good comparison between $TCtrl\text{ON}$ (inner loop) and OFF, the following criteria was used when selecting data series indicated in Figure 9:

- Consistency control with constant set points in both refiners.
- 20 min response time before using the data after a step change in any process variable.
- Low-pass filtered temperature signals decimated from one second to one minute.
- Pulp quality variables measured in KajaaniMAP after the latency chest with a sampling rate of 25 minutes.
- Shortest length of the data series was set to 2 or 4 hours, depending on type of analysis\(^1\).
- When considering operation with temperature control (inner loop only), the set points for $T_{\text{max}}$ must be constant.
- When running the refiners in manual mode the process must be in continuous operation.
- Outliers must be handled properly in both cases\(^2\).

In total, the test procedure for the inner loop covered a period of six days with one change in the feed stock, i.e. a change in the raw material composition, as indicated in Figure 6.

The test procedure for evaluation of the entire $TCtrl$-system, i.e. when also the outer loop was operating, involved longer periods of continuous operations. The selection criteria for data series above was then modified with respect to shortest length and, instead of constant set-point in $T_{\text{max}}$, constant set-point in the controlled quality variable was required.

It is important to compare Figure 6 with other, longer periods in order to get an overview of normal process variability. It is clear that the operating window for the test procedure described above is well within the normal pulp quality specification given in Figure 10. This conclusion is an essential part when proceeding and analyzing the economic impact of introducing a new refiner control strategy.

**Economic considerations**

When it comes to the philosophy of different control concepts, two basic ingredients are often considered. Firstly, the control concept must be able to reduce the variations in the process. Secondly, when the acceptable quality operating window is defined, the control algorithms must be designed to produce a quality within the specification to lowest cost. This is illustrated in Figure 11, for a general refiner control concept using distribution functions. In relation to this work, the lower distribution represents $TCtrl\text{ON}$ and the upper $TCtrl$ OFF and it is obvious that lowest energy consumption is possible to reach if the control concept can guarantee the pulp quality specifications.

In traditional refiner control concepts, however, the lower limits are not often specified. This is a consequence of that increased energy consumption, to a certain point, is believed to produce better pulp quality. This can result in an increased energy input to reach the upper limit even though the pulp quality specification already is met in the lower part of the operating window. If the pulp quality is acceptable within a region spanned by lower and upper limits, it should be regarded as an operating window where the specifications are fulfilled.

From an optimization perspective where also the process economy is taken into account, it would be more relevant to produce a more homogeneous and “good enough” pulp quality, instead of the “assumed” best possible quality. This constitutes a new perspective in refining control and it is a key point of this work.

\(^{1}\) Too short data series destroy the significance in pulp quality measurements.

\(^{2}\) With outliers we mean such measurements which cannot be seen as normal variations due to changes in the process conditions.
RESULTS
Throughout this paper, the reference case called TCtrl OFF corresponds to normal operation with consistency control and manual pulp quality control. TCtrl ON represents the new implementation of the cascade control concept outlined in Figure 5.

The results presented arise from comparisons between data obtained at different conditions. Firstly, the inner loop that controls the maximum temperatures was considered for quality A and B, respectively. Secondly, the outer loop allowing process operation under quality control was analyzed involving two other raw material qualities C and D (where the proportion of saw mill chips was lowest in quality D). In summary, the different operational cases that are discussed throughout the result section are shown in Table 2.

<table>
<thead>
<tr>
<th>Quality</th>
<th>Control mode</th>
<th>Inner loop (Tmax)</th>
<th>Outer loop (Quality)</th>
<th>Length [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>OFF</td>
<td></td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>A</td>
<td>ON</td>
<td>Yes</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>B</td>
<td>OFF</td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>B</td>
<td>ON</td>
<td>Yes</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>C</td>
<td>OFF</td>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>C</td>
<td>ON</td>
<td>Yes</td>
<td>Yes</td>
<td>22</td>
</tr>
<tr>
<td>D</td>
<td>OFF</td>
<td></td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>D</td>
<td>ON</td>
<td>Yes</td>
<td>Yes</td>
<td>30</td>
</tr>
</tbody>
</table>

This rigorous test procedure, which generates the data sets given in Table 2, allows the economical potential to be analyzed in different ways. Here, the following four approaches are considered.

Approach 1: TCtrl ON, inner loop control
Approach 2: TCtrl ON/OFF, inner loop control
Approach 3: TCtrl ON/OFF, outer loop control
Approach 4: Statistical evaluation of TCtrl, inner loop

In approach 1 to 3, the above described procedure of analyzing operating windows are employed, while in approach 4 a more traditional statistical evaluation method is used.

Approach 1: TCtrl ON, inner loop control
Applying the same approach as in Figure 6 and Figure 10, the inner loop of the TCtrl-system can be evaluated, see Figure 12. In terms of pulp quality, the operating window in Figure 12 is smaller when TCtrl is in operation compared with when only consistency control is used. This is notable as, in this case, only the inner loop of TCtrl is used and no quality variable is controlled.

Apparently, the stabilization of the refining zone temperature profile has a positive effect on pulp quality variability. An even narrower operating window than presented in Figure 12 can be obtained if the set-points for the maximum temperatures are not changed as much as in Figure 13.

From Figure 14, it can be seen that the inner loop of TCtrl works sufficiently well. The maximum temperatures follow the set point values as given in Figure 13 within an interval of about +/- 1 °C for the refiners. This can also be illustrated considering differences between the set points (SP) and the process values (PV) as shown in Figure 15.

Even though the set points for the maximum temperatures are changed, according to Figure 13, an acceptable pulp quality is obtained. This indicates that we can study different sets of data within an acceptable operating window when TCtrl is in automatic mode, see Figure 16.

Figure 12: Operating windows describing the pulp quality in terms of CSF and mean fiber length when TCtrl was in automatic mode and in manual mode, i.e. TCtrl ON and OFF.

Figure 13: Operating window for the set points for the maximum temperatures in the inner loop. These are set manually by the operators when the outer loop is not used.

3 These changes were neither a result of the outer loop in the cascade controller, nor could it be related to any planned experiment. Instead the changes were performed by the operators with the purpose of meeting quality demands and to learn more about the inner loop of the TCtrl concept.

4 By tuning the control loops, an interval of +/- 0.5 °C should be possible to guarantee in both refiners.
and an expected operating window can be pre-specified, see Figure 17. From this, a strategy for optimal refiner control can be specified that constitutes a new approach not so often considered by the operators.

The common strategy is to secure pulp quality by, to a certain point, maximizing the energy input to each refiner. We suggest that this strategy should be discarded on behalf of an approach where an operating point closer to the lower limitations is chosen.

Approach 2: TCtrl ON/OFF, inner loop control

If selecting quality B and analyzing the process performance with TCtrl ON and when the traditional consistency controller is used as a standalone controller, i.e. TCtrl OFF, another type of comparison can be performed, see Figure 18.

When comparing the patterns of the maximum temperatures with those for the motor loads, see Figure 19 and Figure 20, it is found that the variables do not offer the same information. This is apparent also when studying data from only TCtrl ON, Figure 14 and Figure 17. Moreover, including data from both TCtrl ON and TCtrl OFF gives a larger operating window compared with the case when only running TCtrl ON. An interval of about 0.65 MW for the primary refiner and 1.5 MW for the secondary refiner is indicated in Figure 20. Naturally, the larger operating window suggests a larger economic potential.

Other ways to describe changes in operating points can be presented as well. One way is to consider the mean value for each population, as described in Figure 21 where a more conservative estimate of the saving potential is given. A change between mean values of the operating points, from the large black to the large white dot in Figure 21, suggests a possible motor load reduction of about 0.14 MW in the primary refiner and 0.40 MW in the secondary refiner.

Further, it is interesting to compare the two sets of data when TCtrl is ON and OFF respectively. During the test period the operators seem to place the controller consistently in automatic mode at a lower maximum temperature in the secondary refiner, compared with the

Figure 14: Operating windows for the process values for the maximum temperatures related to Figure 13.

Figure 15: The difference between the set points (SP) and the process values (PV) in the TCtrl concept.

Figure 16: Acceptable operating windows for the pulp quality when the control concept TCtrl is in operation.

When producing pulp within the acceptable region, the motor load varies considerably for both quality A and B, see Figure 17. If selecting quality B for an analytical overview, motor load variations of about 0.46 MW in the primary refiner and about 1.25 MW in the secondary refiner are found. When more saw mill chips are used, which is the case for quality A, the variations in motor load in both refiners are considerably higher compared when using quality B.

Assume that the maximum temperature in each refiner can be controlled within 1 °C. Approximately, this corresponds to a variation in motor load of 0.25 MW and an expected operating window can be pre-specified, see Figure 17. From this, a strategy for optimal refiner control can be specified that constitutes a new approach not so often considered by the operators.

The common strategy is to secure pulp quality by, to a certain point, maximizing the energy input to each refiner. We suggest that this strategy should be discarded on behalf of an approach where an operating point closer to the lower limitations is chosen.

Approach 2: TCtrl ON/OFF, inner loop control

If selecting quality B and analyzing the process performance with TCtrl ON and when the traditional consistency controller is used as a standalone controller, i.e. TCtrl OFF, another type of comparison can be performed, see Figure 18.

When comparing the patterns of the maximum temperatures with those for the motor loads, see Figure 19 and Figure 20, it is found that the variables do not offer the same information. This is apparent also when studying data from only TCtrl ON, Figure 14 and Figure 17. Moreover, including data from both TCtrl ON and TCtrl OFF gives a larger operating window compared with the case when only running TCtrl ON. An interval of about 0.65 MW for the primary refiner and 1.5 MW for the secondary refiner is indicated in Figure 20. Naturally, the larger operating window suggests a larger economic potential.

Other ways to describe changes in operating points can be presented as well. One way is to consider the mean value for each population, as described in Figure 21 where a more conservative estimate of the saving potential is given. A change between mean values of the operating points, from the large black to the large white dot in Figure 21, suggests a possible motor load reduction of about 0.14 MW in the primary refiner and 0.40 MW in the secondary refiner.

Further, it is interesting to compare the two sets of data when TCtrl is ON and OFF respectively. During the test period the operators seem to place the controller consistently in automatic mode at a lower maximum temperature in the secondary refiner, compared with the
case where only the consistency controller is used, see Figure 19.

Better insight about the pulp quality can be obtained if additional pulp quality variables are studied, beside CSF and mean fiber length. In Figures 22-24, operating windows are presented for shives and selected fiber fractions obtained from the KajaaniMAP. Like for CSF and MFL in Figure 18, a substantial overlap is found between the operating regions for \( T_{Ctrl} \text{ON} \) (black dots) and \( T_{Ctrl} \text{OFF} \) (grey circles). This overlap is characteristic for all studied pulp quality variables, although in the corresponding windows for temperature and motor load well separated operating regions are found.

Figure 18: Operating windows for the pulp quality variations when running the feed stock called quality B, i.e. a lower portion of saw chips to the refiners compared with quality A.

Figure 19: Operating windows for maximum temperatures related to Figure 18.

Figure 20: Operating windows for the motor loads related to Figure 18. Here, the size of the operating window for quality B is about 0.65 and 1.5 MW for the primary and the secondary refiner motor load, respectively.

Figure 21: Operating windows for the motor loads together with mean values when operating with \( T_{Ctrl} \text{ON} \) and \( T_{Ctrl} \text{OFF} \), respectively. The large white dot represents the mean value for \( T_{Ctrl} \text{ON} \) (i.e. for the small black dots) and the large black dot represents the mean value for \( T_{Ctrl} \text{OFF} \) (i.e. for the grey circles).

Figure 22: Operating windows for the pulp quality in terms of shives and MFL obtained from the KajaaniMAP.

Figure 23: Operating windows for the pulp quality in terms of fraction 1 and fraction 3.

Figure 24: Operating windows for the pulp quality in terms of fraction 6 and fraction 3.
**Approach 3: TCtrl ON/OFF, outer loop control**

The inner loop reduces process variations and as well as variations in pulp quality. Besides that, pulp quality can be controlled in a long term perspective by the outer loop of the TCtrl cascade. In this particular installation, the mean fiber length, MFL, was used for feedback. During initial trials freeness, CSF, was also tested as a controlled variable but discharged, as it was observed that the mean fiber length stabilized the process and the pulp quality better.

The operating windows for the maximum temperatures during TCtrl ON are shown for different time series in Figure 25. Two different raw material compositions were used: quality C and quality D, as given in Table 2, where D has the lowest portion of saw mill chips.

From three of the time series (Case 2-4), it can be seen how the control system manages to maintain the maximum temperature within a narrow region although temperature control is now performed by the inner loop of the cascade. For Case 1 the performance is different and a look at corresponding time series reveals changes in the process conditions, see Figures 26 and 27.

Several periods where the mean fiber length is below the reference value can be found, see Figure 26 (for example in the time intervals 2-3 hours and 9-14 hours). Such low MFL values cause the control system to decrease the temperature set-point values and these changes result in the comparably larger operating region in Figure 25 for Case 1. The control performance in Case 1 is however comparable to that of Case 2-4, see Figure 28.

Figure 26 shows how the temperatures levels can be significantly reduced without any notable effect in MFL. From Figure 27 it can be seen that this temperature reduction corresponds to about 1 MW in motor load in each refiner, i.e. in total over 2 MW. Towards the end of this time series, an effect on pulp quality can be noted in form of increased shive values. In a long term perspective, however, a shive level around 0.1% over the mean value is not significantly high, see Figure 29. Thus, it is clear that there is a considerable potential for energy reduction.

---

**Figure 25:** Operating windows for $T_{\text{max}}$ during test of the outer loop of TCtrl. C and D represents different raw material compositions. As an example, Case 3 represents over 17 hours of continuous operation.

**Figure 26:** Time series for variables in Case 1 of Figure 25. Black lines show present values (measurements), grey solid lines show set-point values and grey dashed line show mean value over the time period. From top to bottom: MFL in mm, $T_{\text{max}}$ primary refiner in °C, $T_{\text{max}}$ secondary refiner in °C, shives in %.

**Figure 27:** Time series for the refiner motor loads in Case 1 of Figure 25. The time period is the same as used in Figure 26. The dashed lines indicate mean values for the first and last 2 hours of the time series, respectively.

**Figure 28:** Control error in the maximum temperatures for the cases shown in Figure 25.

**Figure 29:** Shives as function of time during a period of almost a month. The periods considered in Figures 25-28 are from the same month. The mean value for shives in Figure 26 is here shown as a dashed, grey line. The solid, horizontal black line indicates the mean value over the entire period of this figure.
Operation with and without $T_{Ctrl}$ was compared following the same procedure as above when evaluating the inner control loop. For quality D, Figure 30 shows motor load values for about 30 hours of continuous operation with quality control, $T_{Ctrl}$ ON, and about 30 hours of continuous operation with just consistency control, $T_{Ctrl}$ OFF. The size of this operating window is about 1.3 MW for the primary refiner and almost 3 MW for the secondary refiner. For comparison, the window that was discussed when evaluating the inner control loop is indicated (by a gray-shaded rectangle) in the upper right hand corner of Figure 30.

Figure 31 and Figure 32 show the corresponding windows for the variables CSF, MFL and shives. The quality operating window for $T_{Ctrl}$ ON with the outer loop, black dots in Figure 31, is about the same size as the corresponding area for $T_{Ctrl}$ ON with just the inner loop, black dots in Figure 18. Comparing $T_{Ctrl}$ ON with OFF the positive effects of a smaller operating window for CSF and shives was revealed.

Note that the axes in Figures 30-32 show different intervals than the corresponding figures for the inner loop evaluation. The production line was running over a larger region in the operating window during the evaluation of the outer control loop and consequently the results obtained indicate the possibilities of even larger savings if this can be considered as a normal period.

**Figure 30: Operating windows for motor load during test of the outer loop of $T_{Ctrl}$.** The grey rectangle indicates the size and location of the corresponding operating window when using just the inner loop, Figure 29.

**Figure 31: Operating windows for CSF and MFL during test of the outer loop of $T_{Ctrl}$**

It is worth mentioning that if an operating point with unnecessary high energy consumption is chosen during for example a start-up of the refiner line it can take several hours before reaching a more optimal point (see Case 1 in Figure 25). Thus, the operating point that the start-up procedure aims at is crucial. The set-points for the inner loops should preferably be set to the same values as they had prior to a planned shut-down. Thereby, past efforts of the control system are utilized.

**Approach 4: Statistic evaluation of $T_{Ctrl}$**

In the introduction of a new control system the first step is to reduce process variations and the second step involve changes in operating points. This was discussed above and illustrated in Figure 11. Frequently, process variations are quantified by statistical measurements like the standard deviation. The standard deviation is often misused if this can be considered as a normal period.

Results describing the difference in performance with and without temperature control (i.e. $T_{Ctrl}$ ON and $T_{Ctrl}$ OFF) are presented in Table 3. Changes in standard deviations were computed for the different raw material qualities A and B. In this case, data series shorter than 4 hours was excluded as these can give misleading results especially for the pulp quality variables that are measured at a low sampling rate. Regarding mean fiber length and shives, the results are not conclusive. However, a closer look at the numerical values of these standard deviations in the quality B comparison (Table 3) reveals that the indicated changes are not significant in relation to the accuracy of measurement in the KajaaniMAP. As a result, rather than being increased, the variability for these variables should be regarded as unchanged in this case.

To get significant variations in pulp quality it is of interest to compare the process performance with and...
without TCtrl for longer periods of time. One approach is to let TCtrl OFF be represented by time series in Figure 10 which covers a month of normal operation with different feed stock qualities. That period includes raw material changes comparable with quality A and B. Therefore, data representing TCtrl ON is modified so that quality A and B are considered together. The results are shown in Table 4 and a larger effect compared with the results presented in Table 3 is given. Moreover, the results in Table 4 are similar to those presented by Sikter et al [15].

In relation to a statistic evaluation like this, there are several conditions that need careful consideration. It is obvious that the selection criteria for data series, the signal to noise ratio and the signal frequency content all have a significant impact on the results. The latter relates to choices of sampling rate and methods for data pre-filtering. To assure that the result correctly reflects the information of interest, the energy content of the signal has to be concentrated to a relevant frequency region. As an example, the usage of an unnecessary high sampling rate can overshadow important results if the data is not properly filtered [20].

From Table 3 and Table 4, it is easy to conclude that

- the temperature profile is effectively stabilized by the TCtrl inner loop;
- the stabilization of the temperature profiles result in less variation in the refiner motor loads;
- the variations in freeness, mean fiber length and shives are reduced when using TCtrl.

Moreover, during the analysis it was found that even slow trends can have a significant, undesired impact on the standard deviation of a variable. By analyzing time plots of the series taken with quality B (Table 3), it was found that variations in the dilution water flow, which is supposed to control the outlet consistency, had an impact on other process variables. As a result, the comparison with quality B is therefore not fully representative. This is, however, a behaviour that could be expected when dealing with multivariable systems having a high degree of interaction, like the TMP refining process.

| Table 3: Percental changes in standard deviations between operation with TCtrl ON (inner loop) and TCtrl OFF for qualities A and B. P refers to the primary refiner and S to the secondary refiner. A negative value means that the process performs better with TCtrl than without. |
| Change in std | Quality A | Change in std | Quality B |
| TmaxP [°C] | -55% | -13% |
| TmaxS [°C] | -35% | -35% |
| Load P [MW] | -13% | -10% |
| Load S [MW] | -6% | -10% |
| CSF | -43% | -31% |
| MFL | -24% | +8% |
| Shives | -39% | +9% |

Table 4: A comparison where TCtrl ON (inner loop) includes data for both quality A and B. The data representing TCtrl OFF covers a longer time period where raw material changes are included as well.

<table>
<thead>
<tr>
<th>Change in std</th>
</tr>
</thead>
<tbody>
<tr>
<td>TmaxP [°C]</td>
</tr>
<tr>
<td>TmaxS [°C]</td>
</tr>
<tr>
<td>Load P [MW]</td>
</tr>
<tr>
<td>Load S [MW]</td>
</tr>
<tr>
<td>CSF</td>
</tr>
<tr>
<td>MFL</td>
</tr>
<tr>
<td>Shives</td>
</tr>
</tbody>
</table>

In some sense, the configuration of the TCtrl system, as depicted in Figure 5, can be regarded as a simple solution to a difficult control problem. Although the input-output pairing has been made to minimize interaction, the multivariable nature of the process must be dealt with, especially during performance analysis.

**Estimation of economic potential**

It is reasonable, based on the TCtrl performance evaluation, that the system can assure operation within a close region corresponding to a motor load interval of about 0.25 MW in each refiner. To add some margin, consider an interval of 0.30 MW in each refiner.

Figure 20 showed that during the comparison test of the inner loop control, the size of the motor load operating window used was about 0.65 MW for the primary refiner and 1.5 MW for the secondary refiner. Placing the operating region in the most favourable position of this window, i.e. in the lower left hand corner, indicates a savings potential of totally 1.2 + 0.35 = 1.55 MW. Equivalently, Figure 30 that illustrates results from the comparison test of the outer loop control indicates that savings of about 3.5 MW (2.5 + 1.0 MW) is possible for this refiner line.

The mill studied has two refiner lines with the same capacity that operate almost every day of the year. The total yearly production is about 270 000 ADT. For a mill of this size, the above results correspond to a yearly savings potential of about 30 to 60 GWh. In terms of the average energy consumption in the refiners today, the size of the estimated savings corresponds to between 6 and 12%.

**CONCLUSIONS**

In this paper it has been shown how the introduction of a new refiner control system can accomplish stabilization of the process conditions as well as constitute a tool for better energy efficiency. The control system TCtrl is based on a cascade structure where temperature is controlled in the inner loop and the outer loop handles pulp quality in terms of mean fiber length.

The hydraulic pressure is used for controlling the stabilization of the process conditions as well as a new refiner control system can accomplish stabilization of the process conditions as well as constitute a tool for better energy efficiency. The control system TCtrl is based on a cascade structure where temperature is controlled in the inner loop and the outer loop handles pulp quality in terms of mean fiber length.

The hydraulic pressure is used for controlling the stabilization of the temperature profiles, $T_{\text{max}}$. The results show that this gives a stabilization of the entire temperature profile. Thereby, stabilization of motor load and pulp quality variables is also obtained.

References

Sikter et al [15].

CONCLUSIONS
After the process conditions have been stabilized, the outer loop is the tool that assures that the process will operate around a well considered operating point. Naturally, the reduced variability makes it possible to operate closer to boundary values and, as a result, increased energy efficiency can be obtained. This, however, turned out to correspond to a minor part of the full potential that was revealed when analyzing operating windows for this refining process.

Mainly, two types of operating windows were considered: one type describing operating conditions and another describing product quality. The former considers values of $T_{\text{max}}$ or motor load, and these can easily be related to energy consumption. The latter illustrates product quality by considering different combinations of pulp quality variables.

It was found that clearly separated areas in the operating windows for $T_{\text{max}}$ and motor load, corresponds to operating areas showing extensive overlap in the quality variable windows. Thus, a significant hidden potential in the operation of refiner processes has been identified within the windows of accepted quality considered today. The results indicate a saving potential of 30-60 GWh/year for the mill studied.

Finally, a rather extensive statistic evaluation was performed from which only a small portion of the results are presented in this paper. Although the evaluation showed that the process performance is improved by the use of $TC_{\text{ctrl}}$, above all it points out that computing and interpreting standard deviations might not be straightforward. From an evaluation perspective, an operating window approach will give a better picture of the process performance than can a traditional approach using standard deviations. If a complementary method is needed, it is suggested that frequency analysis is performed rather than statistic evaluation.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge STORAENSO, Hylte, and all those who believe that energy demanding processes should be given a chance to be controlled.

REFERENCES


