Refiner Optimization and Control Part IV: Long term follow up of control performance in TMP processes

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KEYWORDS: Refining control, Filtering, Temperature, pulp and paper industry, Decoupling.

SUMMARY: In this paper we will focus on three important issues; Process understanding in relation to control of nonlinear processes; Natural decoupling by using internal state measurement devices; Long term follow up procedures of process control investments.

As an example we will use a new control system for Thermo Mechanical Pulp (TMP) refiners. It is based on a cascaded control structure where the internal states, in this case the refining zone temperature profiles, are controlled in the inner loop whereas the outer loop handles pulp properties. The characteristics of the temperature profile dynamics makes it possible to introduce a decoupling scheme where the anti-diagonal elements in the transfer function matrix describing the process, can be eliminated naturally.

The system is built to handle several pulp propertied simultaneously but in this study mean fiber length (MFL) is the target variable. The process is followed during about 200 days in manual mode control and 200 days in automatic mode in order to evaluate the control performance at different operating conditions. A straight-forward high-pass filtering technique in combination with a threshold selection procedure is introduced for allowing comparison of the data sets from the process. It is shown that the standard deviations in the pulp property variables freeness (CSF) and MFL were decreased about 40 and 60%, respectively. The reduction in variability of shives was approximately 25% when running the process control system and a significant reduction in the motor load standard deviations was also achieved. On top of this process stabilization, an increased production was obtained at the same time as the control system runnability was raised from 50 % to 98 %, levels that are far from commercial MPC-control concepts in TMP refining control.

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During the last decade European pulp and paper industry has moved from a forefront position in newsprint production to a repositioning of the resources to get a better profitability. This has been important for emerging process and control technologies which have much to offer in terms of improved pulp quality and process energy efficiency, Karlström and Isaksson (2009). The reverse of the medal, however, is that many advanced control concepts need much maintenance to reach an acceptable uptime and this problem is one of the important tasks for the control community to address.

Desborough and Miller (2002) concluded in a survey of over eleven thousand controllers in refining, chemical and pulp and paper industries that about two thirds of the controllers had significant improvement opportunity. As about 97 % of all regulatory controllers utilize a PID feedback control concept it means that also rather basic tuning procedures can be improved. Similarly to Desborough and Miller (2002), Harris (1989) showed that a large proportion of control loops in many industries are performing poorly and are capable of much better performance. He stated that the cause of poor performance is not only due to poorly tuned controllers but also valve stiction. This statement is most likely applicable on TMP processes as well and Bialkowski (1993) revealed earlier that as many as 60% of all industrial controllers have some kind of performance problem.

Performance assessment based on minimum variance control, as the standard method for evaluating controllers, has been used for a number of years, Mohieddine (2013), Maciejowski (2002). A long list of articles describing interesting initiative to handle closed-loop performance can be mentioned and one among others which to some extent come back as a natural reference is Harris (1989). He showed a rudimentary procedure how to benchmark the performance of commissioned controllers using industrial plant data without the need for intrusive control experiments.

To overcome the problems, associated with poorly tuned controllers, a vast number of on-line control performance monitoring tools have been proposed see further Hägglund (2005). However, in a plant with many PID control loops, sophisticated systems for analyzing control performance tend to be ignored due to the operators and maintenance staff lack of time on a daily basis. Undoubtedly, intricate process designs in combination with advanced control concepts require experienced application engineers which put a clear focus on strategic organizational issues.

One initial strategy to minimize the risk for investment failure is to rejuvenate and implement state of the art control concepts in order to reach an acceptable control system uptime, Eriksson et al. (2010). In TMP-refining, which will be used as an application example in this paper, control performance needs to be evaluated in a long term perspective and different operating conditions must be considered.

The process computer uptime for advanced refiner control systems is one measure used to describe the control performance. In relation to that, an uptime of 50 to 60% for advanced systems is not good enough when heading for at least 95% availability in automatic mode. One reason for failure to reach an acceptable uptime is that a majority of the sensors in most TMP and CTMP plants are placed outside the refiners due to the harsh environment inside the refining zone, Berg et al. (2003). This makes it difficult to follow and control internal process states vital for a good control performance, see Eriksson and Karlström (2009).

In this paper it is shown how spatially distributed temperature measurements in High-Consistency-refiners can be used to get information that enables a natural decoupling and thereby the applicability of new control concepts, see Karlström et al. (2008), Karlström and Isaksson (2009), Karlström and Eriksson (2014a,b,c,d) and Karlström and Hill (2014a,b).

The first section of the paper comprises the fundamentals regarding the process and suggested process control concept for serially linked refiners. It is also shown how internal temperature measurements can be used for decoupling of subsystems. In addition, control performance in a short term perspective will be discussed briefly as this is a normal procedure for motivating investments. The main task to consider, however, is the control performance in a long term perspective and that will be penetrated in details. Results obtained from a full-scale production line in manual and automatic control will be presented.

Finally, long term follow up procedures of process control investments and economic potential will be given together with a discussion about "good enough product quality" in combination with high energy efficiency in the refiners.

Fundamentals

From a control engineering perspective we start with a simplified description where all disturbances have been excluded, see *Fig. 1*.

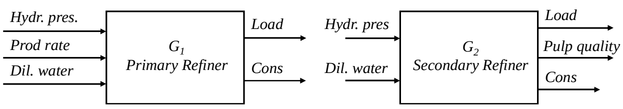

Fig. 1: System description for two serially linked refiners.

The production (wood chip feed rate), dilution water feed rate and plate gap (hydraulic pressure for closing the refining zone) form the inputs. As outputs, the motor loads and consistencies are often considered together with pulp quality. Hence, in its simplest form we have five inputs and at least five outputs[1] to handle.

The production rate is related to the wood chip feed rate to the primary refiner. It is thereby considered as an input while the motor load W_R is an output. In many applications the specific energy, i.e. the ratio between the motor load and production rate is used as an output and a controlled variable which from a control engineering perspective is questionable. For one thing, the production rate is an average estimation and disturbances in the feeding screws will not be possible to handle by controlling the specific energy.

The system described in *Fig. 1* , can be illustrated by the time-invariant model structure

$$y = \begin{bmatrix} W_{R_1} \\ C_1 \\ W_{R_2} \\ C_2 \\ Q \end{bmatrix} = Gu = \begin{bmatrix} g_{11} & g_{12} & & & g_{15} \\ g_{21} & g_{22} & & & g_{25} \\ g_{31} & g_{32} & g_{33} & g_{34} & g_{35} \\ g_{41} & g_{42} & g_{43} & g_{44} & g_{45} \\ g_{51} & g_{52} & g_{53} & g_{54} & g_{55} \end{bmatrix} \begin{bmatrix} h_1 \\ D_1 \\ h_2 \\ D_2 \\ P \end{bmatrix} \tag{1}$$

where C denotes the consistencies in the blow-lines, Q is the pulp quality together with W_R as elements in the vector y. The subscript 1 corresponds to the primary refiner and the subscript 2, the secondary refiner. This simplified system description is useful in many ways and it is obvious that the anti-diagonal elements must be handled with care.

The process is strongly non-linear, a large process operating window must be considered and traditional MPC-concepts have turned out to be difficult to implement with acceptable runnability. Therefore alternative concepts based on measurements of internal states to reach natural decoupling have been proposed; see Karlström and Isaksson (2009). Later studies show that even more rudimentary control structures can be introduced if the temperature profile is measured in the refining zone, see Eriksson et al. (2010).

Natural decoupling: The flow pattern in a refiner is complex, with three physical states (chips, water and vapor) to handle simultaneously. The steam generated in the refining zone is commonly assumed to be saturated, i.e. the pressure is a function of the temperature and vice versa. This assumption is also supported by simultaneous measurements of temperature and pressure, Berg and Karlström (2005). Steam is evacuated both forwards (towards the periphery of the segments) and backwards (towards the inlet), with a stagnation point at some radius in between. This point is assumed to be marked by the maximum temperature (or pressure), since this peak implies zero pressure gradient, $\partial p/\partial r=0$. The maximum can also be described by its temperature T_{max} at the radial position r_{max}, see further description Karlström and Hill (2014c). The shape of the temperature profile differs

[1] The pulp quality can be described by at least three variables but normally only one of these is the prime candidate in control concepts.

considerably dependent on refiner segment design. In summary this implies that several simplifications to *Eq 1* can be introduced. This is best illustrated by studying the low-frequency gains K_{ij} as described in *Fig. 2* where it can be seen that temperature sensors T_4 and T_5 (just below the maximum temperature T_{max}) as process output will give a small gain from the dilution water feed rate D, while the other temperature sensors lead to larger gains.

As seen in *Fig. 2*, the effect on consistency C is small when changing the plate gap (hydraulic pressure, h) and the production rate. Changes in the production rate can affect the outlet consistency considerably, for example, input consistency typically changes a lot when changing raw materials. Altogether, this identifies the hydraulic pressure as a good input candidate.

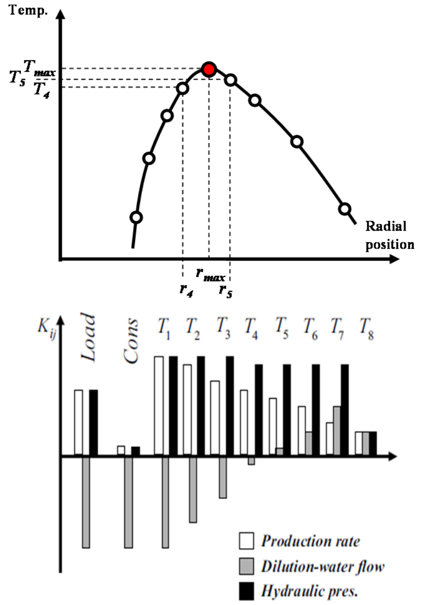

Fig. 2: Low-frequency gains from a primary refiner for different elements in a 10x3- system.

The information given in *Fig. 2* is valuable and constitutes the idea with natural decoupled systems based on internal measurements; see Karlström and Isaksson (2009). Note, the motor loads are in this case replaced by the maximum temperature in the refining zones which forms a clear system description useful for control

$$y=\begin{bmatrix} T_{\max_1} \\ C_1 \\ T_{\max_2} \\ C_2 \end{bmatrix} = Gu = \begin{bmatrix} g_{11} & & & \\ & g_{22} & & \\ & & g_{33} & \\ & & & g_{44} \end{bmatrix} \begin{bmatrix} h_1 \\ D_1 \\ h_2 \\ D_2 \end{bmatrix} \qquad (2)$$

If an MPC- concept is proposed, the pulp quality (Q) in *Eq 1* would be included in this description as output together with the production as an input. Normally, the aim is to keep the production as stable as possible. Any disturbance in production is captured by the temperature profile measurements and by these measurements the refining zone conditions are well reflected in terms of pulp quality variations. As a result, the complexity can be reduced significantly, see Karlström and Isaksson (2009). In case of large intentional changes in production rate, a feed forward controller can be implemented as well but the result of such changes will be detected by the temperature profile and therefore is not included in *Eq 2*.

Hence, in the simplest form, the maximum temperature and the consistency in *Eq 2* can be used for process control in a SISO-system structure for each refiner. Moreover, as stated by Berg et al. (2003) and Karlström (2013), the consistency can be estimated by soft sensors based on the temperature profiles.

Based on *Eq 2* a cascade control system can be proposed where the maximum temperature and the consistency are controlled in an inner loop. This constitutes one part of the basic cascade controller where the outer loop considers one pulp property to be controlled, see Eriksson et al. (2010). Which pulp property to control can differ dependent on mill tradition and most often three candidates are mentioned, MFL (mean fiber length), CSF (Canadian standard freeness) and shives content.

In this paper, we focus on a system where the maximum temperature is controlled in inner control loops for a primary and secondary full-scale Twin refiners and MFL in an outer control loop according to *Fig. 3* and *Table 1.*

The reason why the cascade controller in *Fig. 3* is so attractive can be referred to its rudimentary structure. Some features are not so obvious, like the possibility to split the energy input to the primary and secondary refiners and how to distribute the dilution water to each refining zone, but in general the system is designed to maximize the accessibility and minimize the maintenance of the control system.

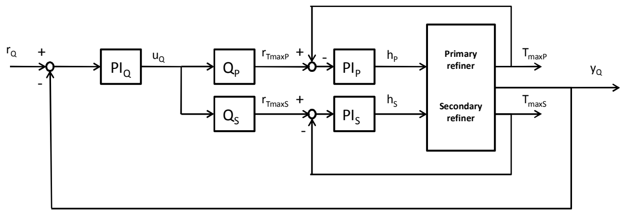

Fig. 3: Schematic drawing of the cascade control concept called TCtrl used for two serially linked Twin-refiners.

Table 1. Description of items referred to in *Fig. 3*.

Notation	Description
r_Q	Reference signal for outer loop, pulp property variable
y_Q	Output signal from outer loop, measured pulp property variable
T_{maxP},T_{maxS}	Maximum temperature in primary (P) and secondary (S) refiner respectively
h_P, h_S	Hydraulic pressures
u_Q	Temperature change to adjust control error
PI_Q	Controller for the outer loop (pulp property control)

PI_P, PI_S	Controllers for the inner loop (temperature control)
Q_P, Q_S	Distribution of the estimated temperature change to each refiner

Results

In a short term perspective the follow up of the improved control performance is straight forward as seen in *Fig. 4* where the inner loop temperatures together with the motor loads are shown in *xy*-plots.

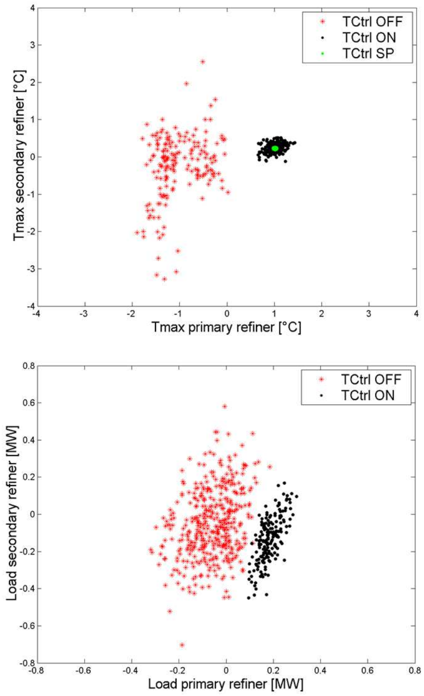

Fig. 4: Upper: T_{max} in secondary refiner vs. T_{max} in primary refiner. Red: TCtrl OFF; black: TCtrl ON; green: set-point for T_{max} during TCtrl ON. Lower: Operating window for the motor loads.

Data from two series of 180 minutes each are shown. One of the series was gathered during operation with temperature control, TCtrl ON, while the other was from operation without temperature control, TCtrl OFF. In this application, the maximum temperatures are allowed to move spatially as well, which suppresses the disturbances in the chip (pulp) feed rate to the refiners.

It is notable that the characteristics of the motor load changes differ from the changes observed in the maximum temperatures. This is a consequence of variations in the fiber distribution inside the refining zone. These variations are impossible to handle if only by controlling external variables like the motor load.

When closing the outer loop, the controller strives towards the MFL set-point. As a result the temperature levels, via the inner loop set-points, are adjusted, see *Fig 5*. This temperature reduction corresponded to a significant reduction in the refiner motor loads, as shown in *Fig 6*. In addition to that, other measured pulp properties were analyzed as well. A comparison with shive content over a longer period, *Fig. 7* revealed that the motor load reduction in *Fig 6* could be performed without violating specifications also for longer periods.

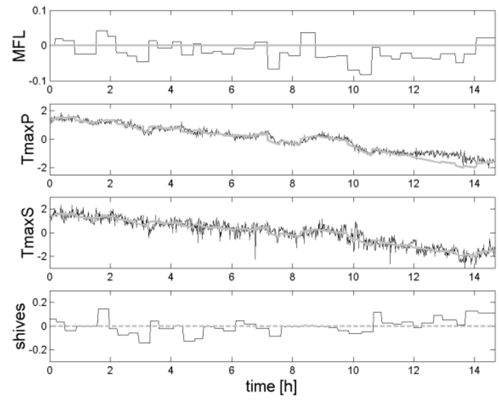

Fig 5: Black lines show present values (measurements), grey solid lines show set-point values and grey dashed line show mean value over the time period. From top to bottom: MFL in mm, T_{max} primary refiner in °C, T_{max} secondary refiner in °C, shives in %.

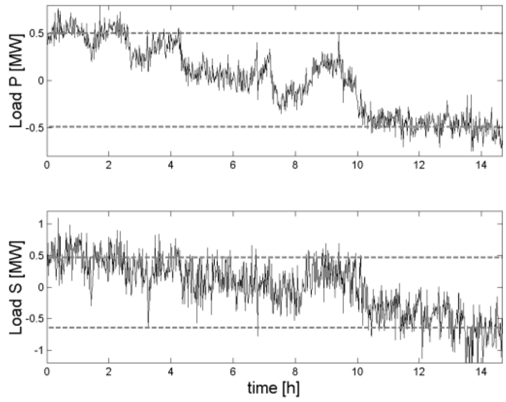

Fig 6: Time series for the refiner motor loads during a test period. The dashed lines indicate mean values for the first and last 2 hours.

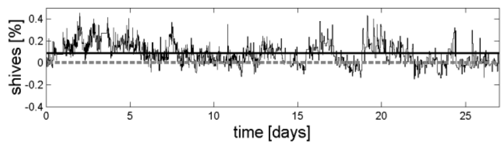

Fig. 7: Shives values for a period of almost a month. The period considered in Figures 5-6 is from the same month. Dashed, grey line: shives mean value from period described in *Fig 6*. Solid horizontal black line: mean value in this figure.

In a long term perspective, however, the follow up becomes more complex as it requires attention from the organization as well as the suppliers of equipment and software. Analyzing processes over a long period also means that events like scheduled stops, e.g. changes of refining segments, which are planned and performed about five to six times per year. Unpredictable production stops such as plate clashes, start-up procedures, different production levels and variations in feedstock must be considered as well when analyzing longer periods.

However, long term follow up protocols of process control investments have proven to be necessary to find economic potentials also for future investments. When analyzing long periods with complex process information, a robust data selection procedure for threshold settings must be introduced. The constraints chosen can be defined as

$$x_{\min_i} \le V_i \le x_{\max_i} \qquad i = 1,2,\ldots,n$$

where the lower and upper limits are set by normal refiner line operation. The variables V_i typically comprise refiner motor loads, production rate, the controlled pulp quality and maximum temperatures in each refining zone if available, see further discussion in Appendix A.

Consider a generic system description of the cascaded control system shown in *Fig. 8*.

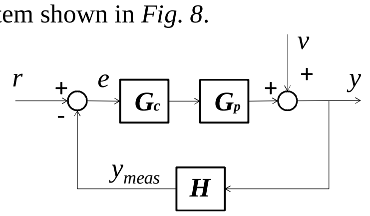

Fig. 8: Simplified system description of the inner loop in a cascade control concept given in *Fig. 3.*

The process value possible to measure, y_{meas}, is often expressed as the summary of the expected process value y and the disturbances, v, occurring in the process. The measurement device is often described by a function H which normally is described as a transfer function with or without measurement delays. Hence, the measured process value is filtered through H.

The control error, e, plays an important role in all methods analyzing control performance in processes. From a signal processing perspective, this error is the input to the system to be analyzed and filtered via the functions G_c which describes the controller and the G_p i.e. the process transfer function which also includes actuators and possible saturations in valves etc.

In processes which are well designed and tuned the problems in valves and saturation due to limitations in actuators are normally negligible. This means that we have a rather traditional system description which can be represented by the equations

$$\begin{aligned} & y = G_C G_P (r - y_{meas}) \\ & y_{meas} = H(y - v)) \\ & \Rightarrow \\ & y_{meas} = \frac{H(G_C G_P r - v)}{1 + H G_C G_P} \end{aligned} \qquad (3)$$

where the delay is incorporated in G_p.

As the control error can be seen as a simple high-pass filtered signal, a comparison with a high-pass filtered process value y_{meas} can be performed since this will eliminate the effects of trends in the process variables. However, the introduction of a high-pass filter, by using e.g. a 4th order Butterworth filter, requires a specified cutoff frequency, defined as the break frequency which divides the signal into one low-pass filtered signal and one high-pass filtered signal. The cutoff frequency, ω, must be chosen in the interval $0.0 < \omega/\omega_n < 1.0$ where ω_n is the so called Nyquist frequency which corresponds to half the sampling rate[2]. In the interval specified above the upper limit 1.0 corresponds to half the sampling rate and one way to find a suitable cutoff frequency is to minimize the correlation coefficient, i.e.

$$K = \mathrm{cov}(e, Y_{meas}) / \sqrt{\mathrm{cov}(e, e)\,\mathrm{cov}(Y_{meas}, Y_{meas})} \qquad (4)$$

between the control error (e) and the high-pass filtered process value (Y_{meas}). It is important to compensate for known disturbances and delays in the measurement device before calculating the covariance matrices.

In this paper we will focus on two consecutive periods TCtrlOFF and TCtrlON comprising 30000 samples each. The samples are averaged every 10 minutes and this means that 208 days are covered in each set. Especially trends are a problem when following such long periods as the low-frequency variations affect the statistical measures negatively. For refining processes controlled in automatic mode, this is not a problem as we can follow the setpoint changes but in manual mode it is much harder to follow the process changes performed by the operators as these are normally not included in the history data base.

Analyzing the control error, in MFL using a histogram is one way. In *Fig. 9*, it is seen that the control error is small (about +/- 0.1-0.15 mm in MFL variation). This implies that the control performance is acceptable over a large range of operating conditions.

If this method is applied on two signals from the sets described by TCtrlON, one which describes the control error of MFL in time domain *(X)* and one which relates to the high-pass filtered MFL *(Y),* a good correlation can be extracted for specific cutoff frequencies. In *Fig. 10*, the correlation coefficients between these two signals are

[2] A fundamental result in signal processing, the sampling theorem, states that any sampled signal can only properly reflect variations in the variable which are slower than half the sampling rate, see Ljung (1999).

shown versus the ratio of the cutoff frequency to the Nyquist frequency, i.e. ω/ω_n.

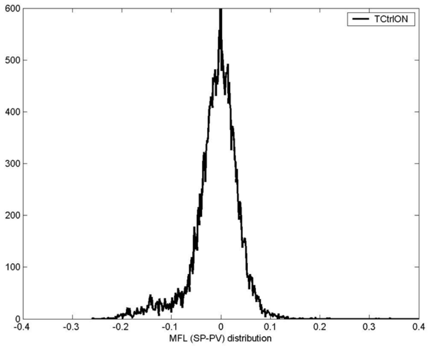

Fig. 9: Control error in terms of a histogram for the entire set of data when running the system in automatic mode.

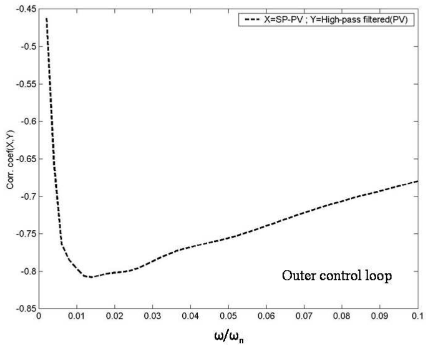

Fig. 10: The correlation coefficients between the control error (SP-PV) and high-pass filtered (PV) for MFL versus the cutoff frequency for a set of samples (sampling rate = 10 minutes).

The obtained high-pass filtered process value, using ω/ω_n=0.025, is shown in *Fig. 11* which also seems to be acceptable even though the best correlation is obtained for 0.0125. Now when a proper cutoff frequency is obtained, high-pass filtering of data can be applied on the period when running the process in manual mode (TCtrlOFF). Thereby, the trends are rejected from both data sets and traditional statistical methods can be applied.

In *Fig. 12*, the box-and whisker diagram, for the two high-pass filtered data sets TCtrlOFF and TCtrlON using the cutoff frequency of $0.0125\omega_n$ is given.

To handle dynamic variations in the process, the standard deviations of the high-pass filtered MFL at different threshold settings for acceptable process variations are given, see *Fig. 12*, i.e. the samples larger than the threshold settings is rejected and not included in the estimation of the standard deviation.

In *Fig. 12* it is obvious that the process variations are larger for TCtrlOFF compared with TCtrlON. The accepted interval according to *Fig. 9* is 0.1-0.15 mm is marked in the *Fig. 12* as dotted lines and exceeds the whisker settings. However when running in manual mode, the variations in MFL are normally much larger and the interval is set based on TCtrlON and not the situation outlined by TCtrlOFF, see Appendix A.

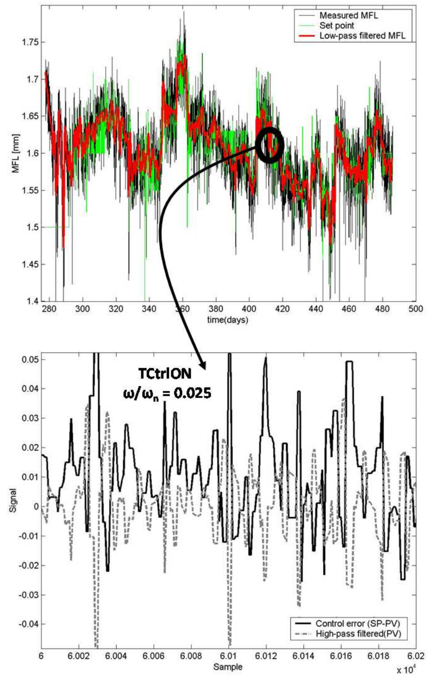

Fig. 11: Upper figure: The set-point and measured value of MFL, and low-pass filtered MFL versus time. Lower figure: The control error and the high-pass filtered process value.

When controlling MFL in the outer loop the variation in other pulp properties are reduced as well, for example CSF according to *Fig. 13*.

In pulp and paper industry a distribution of +/- 50 ml in CSF will seldom result in compensation claims by the customers. Sometimes it is claimed that more paper breaks in the paper machine occurs when the CSF distribution is too wide, but it is hard to confirm the breakage due to large CSF variations.

Here, a fairly conservative measure based on the lower and upper whiskers as limits is considered. In *Fig. 14*, which is based on the data series for the high-pass filtered CSF, using the same cutoff frequency of $0.0125\omega_n$ as above, the difference between the upper and lower whiskers corresponds to a threshold interval of +/-30 ml for TCtrlOFF, which is reasonable to accept. When running the process in automatic mode (TCtrlON) the threshold is about +/- 15 ml.

The information given in *Fig. 12* and *Fig. 14* is related to the outer loop of the cascade, but these improvements are a result of the inner loop control performance. This is shown in Appendix B where the same statistical approach as outlined above is used for the maximum temperature in the secondary refiner. As a consequence of the temperature control, the motor load will be stabilized as well, see Appendix B.

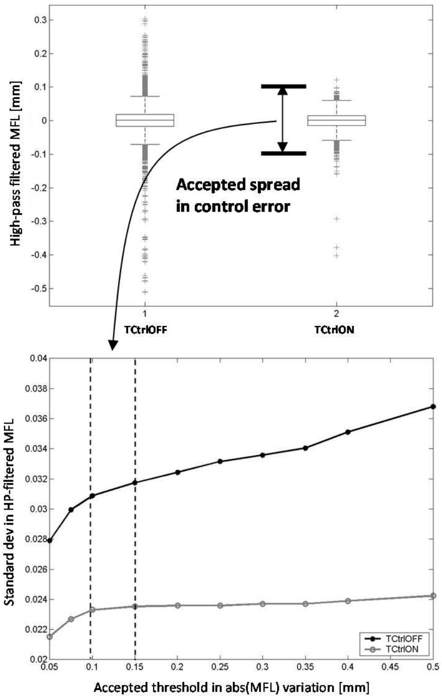

Fig. 12: Upper figure: Box plot for the high-pass filtered MFL (ω/ω_n=0.0125) according to the data sets TCtrlOFF and TCtrlON, respectively. Lower figure: Standard deviations in the high-pass filtered MFL (ω/ω_n=0.0125) versus accepted threshold for TCtrlOFF and TCtrlON.

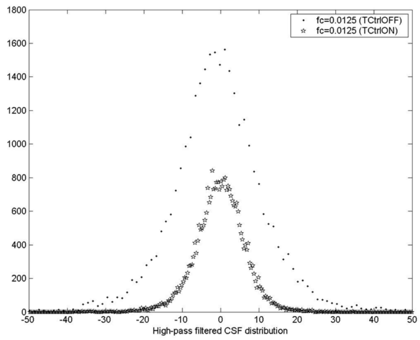

Fig. 13: The distribution in the high-pass filtered CSF for the entire populations TCtrlOFF and TCtrlON shown in Appendix A.

Hence, using the method described above, the high-pass filtered variables can be interpreted as measures for analyzing the control performance. Low-pass filtered variables describe the process conditions in a long term perspective and relates to the maintenance of refiners and auxiliary equipment.

In *Table 2*, a summary of the main results are given. As seen, variations in the process variables are significantly reduced when running in automatic mode (TctrlON). In the column describing the lowpass filtered ratios, it is obvious that the operators run the process in a much larger operating window during TCtrlOFF compared with TCtrlON. This is probably true for all variables except the motor load in the primary refiner which is running on the edge of its capacity. The mean values for the entire data sets are, however, similar which indicates that the process data over a long period is obtained in rather well specified operating window.

Besides the reduction in process variations when running TCtrlON, it is also interesting to study the production level and the process uptime. As seen in Appendix A, a slightly larger production of 1 tonne per day and process line is obtained when running TCtrlON. This is a direct consequence of the reduced variations in the refiner motor loads.

Introduction of thresholds for production stops according to Appendix A indicates less process downtime based on the process data obtained. This corresponds to about 3-7 days production loss on a yearly basis for one production line when running TCtrlOFF compared with TCtrlON. The uncertainties in such measures are a consequence of the difficulties and tedious work to synchronize information obtained from the data sets with information extracted from the log books.

Lastly, it should be stressed that fact that the mean values of the variables studied in each set are more or less unchanged, see *Table 2* indicates a strategic possibility to take the next step towards lower energy consumption while maintaining the pulp properties within an acceptable specification.

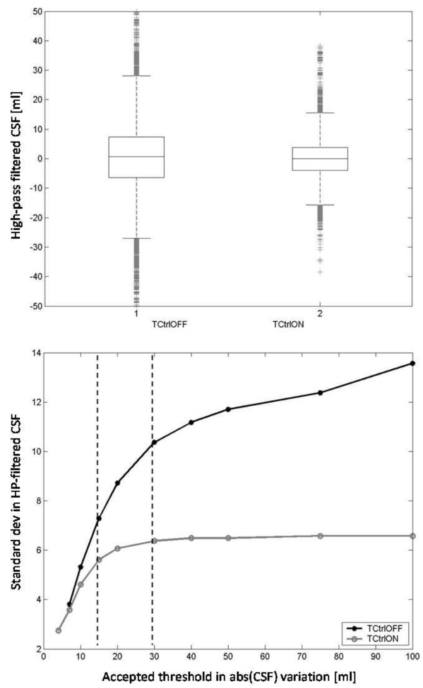

Fig. 14: Upper figure: Box plot for high-pass filtered CSF (ω/ω_n=0.0125). Lower figure: Standard deviations in the high-pass filtered CSF (ω/ω_n=0.0125) versus accepted threshold.

TABLE 2: Ratios of standard deviations for the high-pass filtered and low-pass filtered variables when running TCtrlOFF and TCtrlON.

Measured variables	Ratio between the HP-filtered standard dev. for TCtrlOFF and TCtrlON	Ratio between the LP-filtered standard dev. for TCtrlOFF and TCtrlON	Mean value ratio TCtrlOFF/TCtrlON
MFL	1,33	1,37	0,99
Shives	1,11	1,12	0,98
CSF	1,91	1,12	1,01
Motorload(Prim)	1,07	0,90	1,01
Motorload(Sec)	1,37	1,19	0,99
Tmax(Prim)	1,09	1,28	1,01
Tmax(Sec)	1,78	1,58	1,00

Conclusions

In this paper it has been shown how the introduction of a new refiner control system based on natural decoupling can accomplish stabilization of the process conditions as well as constitute a tool for better energy efficiency. Special emphasis is put on the long term follow up procedures of the process control investments in order to identify the economic potential also for future investments.

To follow large sets of data a special high-pass filtering technique is introduced. The cutoff frequency for the controlled variable MFL is chosen according to the obtained control error for a well-tuned cascade control system. It is shown that a good comparison between different data sets can be established using the method. As a consequence of the method chosen, it is shown that the standard deviations in MFL and CSF are reduced about 40-60 % when using the new control concept. Reductions in variations of other pulp properties are obtained as well. As an example, in this study the standard deviation in shives was reduced about 10-25 %. However, recent experience has shown that the potential for improvements are even larger if considering shives instead of MFL as the controlled variable.

Improved stability in the process conditions can be seen through less motor load variations, especially for the secondary refiner. However, the considerable stabilization of the refining zone conditions is not fully reflected by the motor load variations, but clearly captured by the sensors placed inside the refining zone. The variations in the maximum temperature is reduced by at least 50% for the secondary refiner and by about 10% for the primary refiner when running the process in automatic mode compared with manual mode. This is probably the reason for the dramatically reduced variations in pulp properties. As seen in *Table 2*, the reduction in temperature variation is less in the primary refiner compared with the secondary refiner and, again, this is a consequence of the production limitations of this specific refiner.

We can also conclude that the production rate could be increased by about 1 tonne per day when controlling the process. This is of course not so impressive but at the same time, due to the increased process stability, the production downtime will be reduced. The study gave an estimate of about 6 days on a yearly basis when running two production lines with the TCtrl concept. This corresponds to about 2400 tonne increased pulp production annually.

An extensive potential for energy savings, within the windows of accepted pulp properties, exist as well. In summary, the following can be stated: It is shown that without violating specifications in the pulp properties the total power supply to a production line can be reduced at least 2 MW from the average of 30 MW. This means a saving potential of about 35 GWh/year for the mill studied, probably more, if using the full potential of the new control concept. Using an emission factor of 375 tons CO_2 per GWh for natural gas combined cycle (marginal electricity) this means about 13 000 tons less emissions to atmosphere per year, Sikter (2007). Normally the documented emissions are obtained from coal condense fossil-fuel power plants available today, Sikter (2007). If this traditional technology is used the emissions are increased to 39 000 tons per year.

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Appendix A

All control situations analyzed in this paper, are visualized in *Fig. 15*. Note that about 80000 samples, averaged on a 10 minute basis, are covered, i.e. we can analyze data for about 555 days. For the control case, the periods where the outer loop was in operation, i.e. TCtrlON (outer loop), will be considered. For this, 30000 samples are selected corresponding to about 208 days.

We introduce the following constraints to describe normal refiner line operation.

- 14 MW < Motor load (prim. ref.) <19 MW
- 11 MW < Motor load (sec. ref.) <16 MW
- *Tmax* (both refiners) > 165 °C
- Production > 350 ADMT/day
- 1 mm < MFL < 1.8 mm

After this reduction, we get two different data sets, TCtrlOFF and TCtrlON for which the motor loads and the maximum temperatures in the refining zones are as shown in *Fig. 16*. It is clear that a range of operating conditions in a multivariable operating window is covered. The variations in operating conditions are primarily a consequence of the wearing of the refining segments but also that variations in e.g. dilution water feed rate and production level, as well as the feedstock, are present. Naturally, such variations can affect the analysis and should be carefully considered.

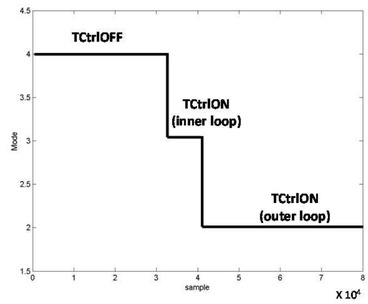

Fig. 15: Periods with three different control modes. TCtrlON has two different modes, that is when just the inner loops are closed, and when both the outer and the inner loops are closed. This series corresponds to about 555 days.

Variations in the feedstock composition are often referred to by the amount of wood chips from saw mills that are fed to the refiners. It is difficult to conclude how these variations affect the refining conditions just by studying *Fig. 16* and *Fig. 17*.

The process data that were excluded by the constraints given above relates to situations where we have a production stop or a startup of a production line. When the motor loads in the primary and secondary refiners are less than 3 MW, the production line is expected to be down for service and longer maintenance activities. From this, it is easy to obtain the time for the production stops.

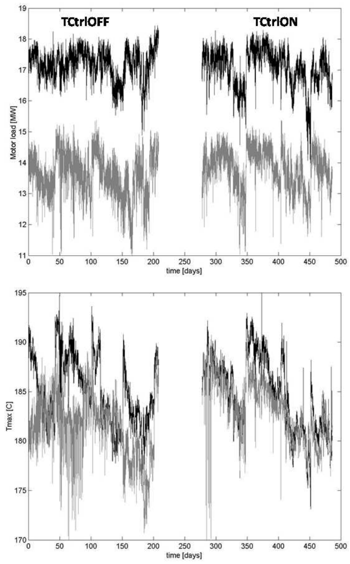

Fig. 16: Motor loads and maximum temperatures for two serially linked refiners versus time when running TCtrlOFF and TCtrlON. Black and grey lines correspond to the primary and secondary refiners, respectively.

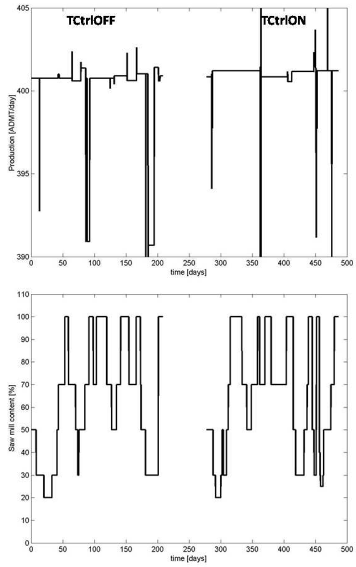

Fig. 17: Production and saw mill chip content versus time when running TCtrlOFF and TCtrlON.

When the motor load is less than 14 MW for the primary refiner and less than 11 MW for the secondary refiner, a startup of the process is expected. Although these periods could be classified as production stops or non-normal operation, the approach applied in this paper is conservative. Still, on a yearly basis the comparison implies about 3-7 days production loss for one production line when running TCtrlOFF compared with TCtrlON.

It is even more difficult to foresee the chip mixture impact on the pulp properties in terms of CSF and MFL, see *Fig. 18*. This is notable; as it is considered well established that the pulp properties are affected considerably when changing the feedstock composition.

Here, MFL will be considered as the controlled variable in the outer loop described in *Fig. 3*, but for this specific application it has been shown that shives are also possible to control setting thresholds on MFL and CSF. Traditionally, CSF has been the preferred control variable. In this study it was found that the CSF measurements generated so many outliers that an acceptable control performance could not be obtained.

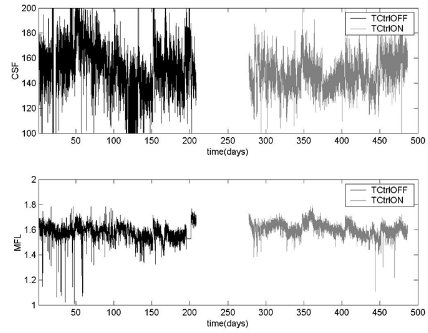

Fig. 18: CSF and MFL versus time when running TCtrlOFF and TCtrlON.

Appendix B

The inner loop control is supposed to maintain the maximum temperature of the temperature profile at a specified level by manipulating the plate gap (hydraulic pressure). The maximum temperature is allowed to move spatially as it is closely linked to the steam turning point where the steam moves backwards and forward in the refining zone. This result in a situation where natural decoupling of the MIMO-system is obtained and by this, two SISO-loops, one for controlling the maximum temperature and one for the consistency control, could be implemented for each refiner. All this is thoroughly described in the main section and in this Appendix, the temperature and motor load are high-pass filtered using the same principals as outlined above.

In *Fig. 19* and *Fig. 20* it can be seen that the stabilities are significant improved when the new control concept given in this paper is introduced.

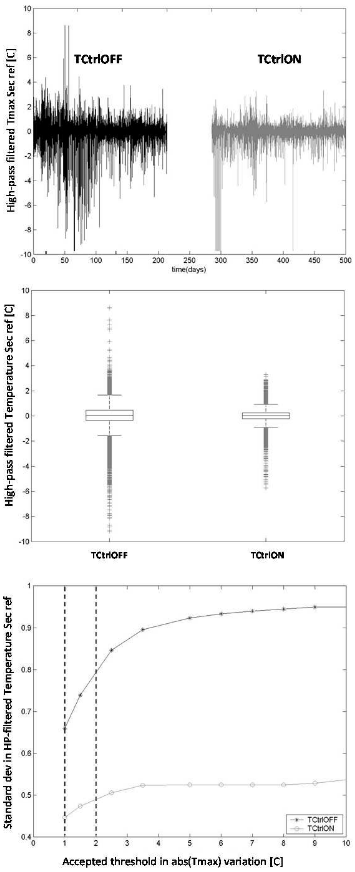

Fig. 19: Upper figure: Maximum temperature in the secondary refiner versus time for the data sets TCtrlOFF and TCtrlON. Middle figure: Box plot for the high-pass filtered T_{max} (ω/ω_n=0.0125) according to the data sets TCtrlOFF and TCtrlON, respectively. Lower figure: Standard deviations in the high-pass filtered T_{max} (ω/ω_n=0.0125) versus accepted threshold for TCtrlOFF and TCtrlON.

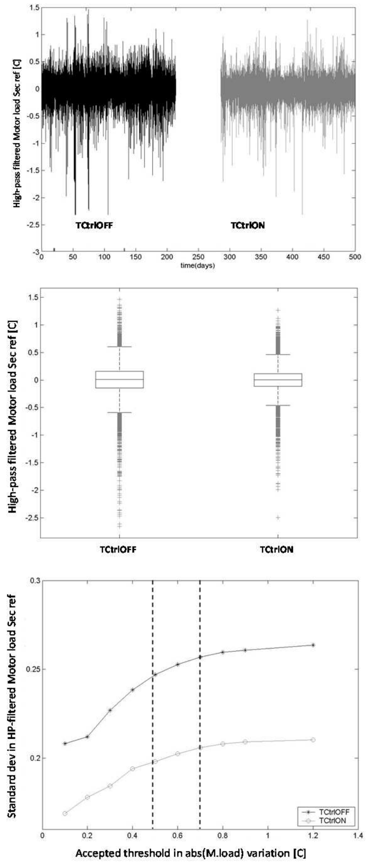

Fig. 20: Upper figure: Motor load in the secondary refiner versus time for the data sets TCtrlOFF and TCtrlON. Middle figure: Box plot for the high-pass filtered motor load (ω/ω_n=0.0125) according to the data sets TCtrlOFF and TCtrlON, respectively. Lower figure: Standard deviations in the high-pass filtered motor load (ω/ω_n=0.0125) versus accepted threshold for TCtrlOFF and TCtrlON.