Long term follow up of control performance in TMP processes

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Abstract: 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 – The idea is to use rudimentary controllers with reliable runnability before entering more sophisticated control concepts; Long term follow up procedures of process control investments – An important issue when identifying the economic potential of future investments.

As an example we will use a new control system for Thermo Mechanical Pulp (TMP) refiners, one of the most demanding non-linear processes in the pulp and paper industry. 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. Hence, the idea is to control this complex and nonlinear process with serially linked refiners using basic control loops to improve the runnability. At the time of writing, an MPC-concept for overall TMP-plant optimization is discussed.

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 available on the market.

Keywords: Control, Filtering, Temperature, Pulp and Paper industry, Decoupling.

1. INTRODUCTION

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 runnability 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 that means that also rather basic tuning procedures can be improved.

To overcome the problems, associated with poorly tuned controllers, a vast number of on-line control performance monitoring tools have been proposed, e.g. 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, a runnability of 50 to 60%

for advanced systems is not good enough when heading for at least 95% availability in automatic mode of the process uptime. One reason for failure to reach an acceptable runnability is that a majority of the sensors in most TMP and CTMP plants are placed outside the process equipment 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 temperature measurements in a High-Consistency-refiner can be used to get information that enables a natural decoupling and thereby the applicability of new control concepts, Karlström et al. (2008), Karlström and Isaksson (2009).
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 quality" in combination with high energy efficiency in the refiners.

2. FUNDAMENTALS

2.1 Process description

The pulp and paper industry is always seeking new opportunities to become more energy efficient. Fuel switching is one such opportunity for those facilities that use more than one form of energy or fuel. Maximizing the overall energy efficiency at a facility may often lead to net reductions in one form of energy (*e.g.,* natural gas, fuel oil or coal) while at the same time increased consumption of another (*e.g.,* electricity). How to model these options and thereafter optimize a complete mill is a challenging task.
From an energy balance perspective a simplified model can be formulated using the scheme described in Fig. 1.

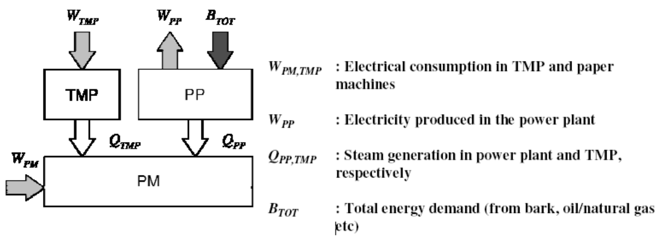

Fig. 1. Schematic overview of a newsprint mill from an energy perspective.

This model can thereafter be coupled to different product considerations which are affected by the material and energy balances. Often a plant for recycled fiber supply exists as well, but this is not included in Fig. 1 as it stands for a minor energy sink of the total mill economy.
The TMP process stands for about 70% of the electricity consumption in the mill and it varies considerably over time. Therefore, it is essential to optimize the main consumers, the refiners, from an overall energy consumption perspective.
The electricity consumption in the TMP process affect the steam balance directly as the refiners are the main producers of steam to the plant. Therefore even small deviation from desired operating set points in the TMP process will affect the energy balance as well as the product properties.
Dynamic considerations are best described by differentiating the electrical consumption in the mill, W_{TOT} , with respect to time and the vector u containing the elements P representing the production rate of pulp in the refiners, h the hydraulic pressure applied on the refiner discs[1] and D the dilution water feed rate.

$$
\begin{aligned}
&W_{TOT} = f(u) \quad ; \quad B_{TOT} = g(u) \quad ; \quad u = [P, h, D]^T \\
&\frac{\partial}{\partial t}(W_{TOT}) = \frac{\partial}{\partial u}(W_{TOT}) \cdot \frac{\partial}{\partial t}(u) \quad ; \quad \frac{\partial}{\partial t}(B_{TOT}) = \frac{\partial}{\partial u}(B_{TOT}) \cdot \frac{\partial}{\partial t}(u)
\end{aligned}
\qquad (1)
$$

In order to describe the differentiated forms of W_{TOT} and B_{TOT} with respect to the vector u, material and energy balances from the TMP must be derived. Dynamic changes in the vector elements in u can be seen as measurable inputs to an overall optimizer and therefore straight forward to handle..
The major part of W_{TMP} is associated with the energy consumption in the refining processes, i.e. $W_{TMP} \approx \Sigma W_R$ where W_R is the electrical consumption in each refiner. Thereby, all residuals related to pumps et cetera is considered as relatively constant over time.
A common TMP process configuration has two serially linked refiners in each production line and the final pulp quality is dependent on each refiners operation.
The refiner control strategy differs from one mill to another. Refining is well known to be a complex process with many disturbances and interactions. In some cases, refiners have an internal interconnection, in terms of piping from the outlet to the inlet, which makes control even more challenging.
From a control engineering perspective we start with a simplified description where all disturbances have been excluded, see
Fig. 2.

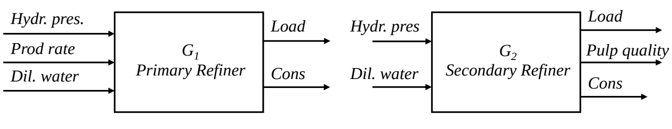

Fig. 2. System description for two serially linked refiners.

The production (wood chip feed rate), dilution water feed rate and plate gap (hydraulic pressure for closing the refining zone) forms the inputs. As outputs, the motor loads and

[1] In many TMP refiners, plate gap sensors are implemented and can be used instead of the hydraulic pressure if the measurements are reliable.

consistencies are often considered together with pulp quality. Hence, in its simplest form we have five inputs and at least five outputs[2] to handle.

The production rate is related to the wood chip feed rate to the primary refiner. It is thereby, according to Fig. 2, 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. 2, can be illustrated by the time-invariant model structure

$$y=\begin{bmatrix} W_{R_1} \\ C_1 \\ W_{R_2} \\ C_2 \\ Q \end{bmatrix} = Gu = \begin{bmatrix} g_{11} & g_{12} & & & g_{15} \\ g_{21} & g_{22} & & & g_{25} \\ g_{31} & g_{32} & g_{33} & g_{34} & g_{35} \\ g_{41} & g_{42} & g_{43} & g_{44} & g_{45} \\ g_{51} & g_{52} & g_{53} & g_{54} & g_{55} \end{bmatrix} \begin{bmatrix} h_1 \\ D_1 \\ h_2 \\ D_2 \\ P \end{bmatrix} \qquad (2)$$

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).

2.2 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}) and radial position (r_{max}). A typical temperature profile and pressure gradient is shown in Fig. 3.

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

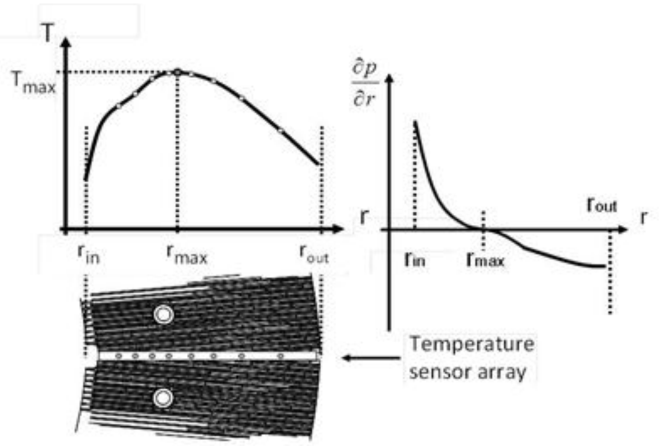

Fig. 3. A typical temperature profile, and corresponding pressure gradient, from a primary refiner where a sensor array is placed between two refining segments.

If for instance the pressure gradient at some point is not enough to let steam evacuate at the same rate as new steam is formed, steam will be accumulated, which will increase the pressure and the pressure gradient locally. If instead the pressure gradient is too high, the pressure gradient will decrease. These mechanisms act to bring the process back to the stable state. However, such phenomenon changes the fiber pad distribution and in the short term perspective the entire fiber pad profile can be changed dramatically, see Karlström (2013). Therefore, in an overall perspective where the entire refiner is studied, such situation can result in different pulp properties at the same motor load. This is normally not considered in traditional refiner control concepts.

The segment pattern, schematically given in Fig. 4a, is one of the most important parameter to set for different types of fiber qualities as it relates to the fiber impact as well as the distance between the segments mounted on the rotor holder and the stator holder, see Fig. 4b.

A large taper results in a larger distance between the two segments and forces the temperature profile outwards the periphery while a more narrow taper will force the profile temperature maximum closer to the center of the plates, see Fig. 4c. All these aspects affect the control strategy and it is important to select segments to maximize the control runnability to reach optimized process stabilization.

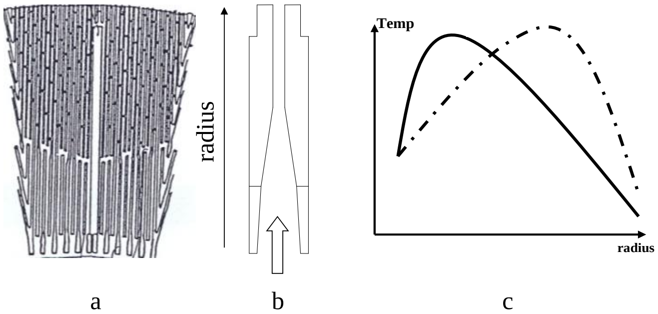

Fig. 4. a) A typical section of a segment where the pattern is visualized together with the sensor array for temperature measurements. b) Cross-section of two segments, on the

stator and rotor position respectively. The taper is shown as the distance between the two segments. c) Temperature profiles for two different tapers. Dash dotted line corresponds to segments with a large taper ("open" segments).

Other nonlinearities, like refining segment wear occur as well and introduce some problems in traditional control concepts based on the system description in eq. 2. However, by using the maximum temperature from the temperature profile in Fig. 3 and Fig. 4 a new control concept based on natural decoupling can be introduced. This is best illustrated by studying the low-frequency gains K_{ij} as described in Fig. 5 where it can be seen that temperature sensors T_4 and T_5 as process output will give a small gain from the dilution water feed rate D, while the other temperature sensors lead to larger gains.

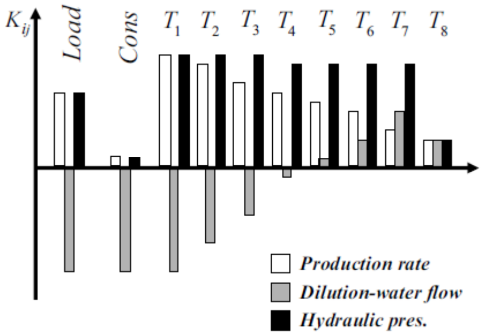

Fig. 5. Low-frequency gains from a primary refiner for different elements in a 10*x3*- system.

As seen in Fig. 5, 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.

The information given in Fig. 5 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

$$y = \begin{bmatrix} T_{\max_1} \\ C_1 \\ T_{\max_2} \\ C_2 \end{bmatrix} = Gu = \begin{bmatrix} g_{11} & & & \\ & g_{22} & & \\ & & g_{33} & \\ & & & g_{44} \end{bmatrix} \begin{bmatrix} h_1 \\ D_1 \\ h_2 \\ D_2 \end{bmatrix} \qquad (3)$$

If an MPC- concept is proposed, the pulp quality (Q) in eq. 2 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) and Karlström and Eriksson (2013). 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 not included in eq. 3.

Hence, in the simplest form, the maximum temperature and the consistency in eq. 3 can be used for process control in a SISO-system structure for each refiner. Moreover, as stated by Berg et al. (2003) and Karlström and Eriksson (2013), the consistency can be estimated by soft sensors based on the temperature profiles.

Based on eq. 3 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. 6 and Table 1.

The reason why the cascade controller in Fig. 6 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.

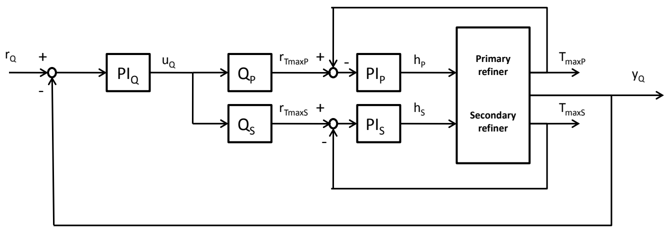

Fig. 6. Schematic drawing of the cascade control concept called *TCtrl* used for two serially linked Twin-refiners.

Table 1. Description of items referred to in Fig. 6.

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

2.3 Analysis of control performance

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). Harris (1989) showed how to benchmark the performance of commissioned controllers using industrial plant data without the need for intrusive control experiments.

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.

The focus in most research journals is to improve the tuning of existing controllers. This is not the scope of this paper which calls attention to the long-term evaluation of the control performance.

Hence, the key question in this paper is to address how the performance of an implemented control system in a short and long term perspective and how to relate the process control investment to earlier control concept.

3. RESULTS

In a short term perspective the follow up of the improved control performance is straight forward as seen in Fig. 7 where the inner loop temperatures together with the motor loads are shown in *xy*-plots.

Data from two series of 180 minutes each are shown and 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 suppress the disturbances in the chip (pulp) feed rate to the refiners.

It is notable that the characteristics of the motor load changes are different than the changes observed in the maximum temperatures. This is a consequence of variations in the fiber distribution inside the refining zone, variations that 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. This temperature reduction corresponded to a significant reduction in the refiner motor loads, as shown in Fig 9. In addition to that, other measured pulp properties were analyzed as well. A comparison with shive content over a longer period, Fig. 10 revealed that the motor load reduction in Fig 9 could be performed without violating specifications also for longer periods.

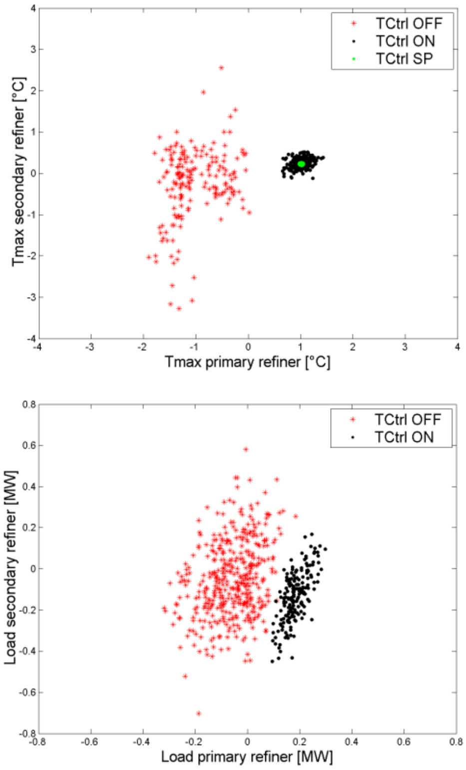

Fig. 7. Upper: T_{max} in secondary refiner vs. T_{max} in primary refiner. Red: *TCtrl* OFF; black: *TCtrl* ON; green: set-point for T_{max} during *TCtrl* ON. Lower: Operating window for the motor loads.

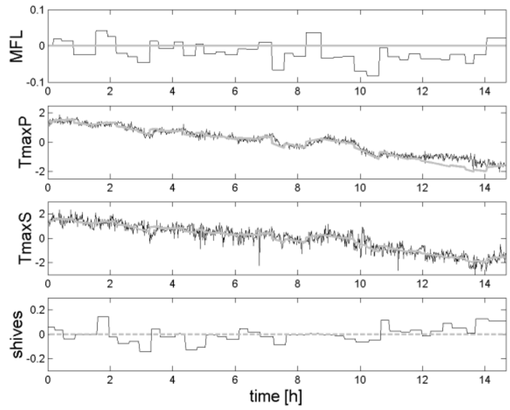

Fig 8. Black lines show present values (measurements), grey solid lines show set-point values and grey dashed line show mean value over the time period. From top to bottom: MFL in mm, T_{max} primary refiner in °C, T_{max} secondary refiner in °C, shives in %.

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.

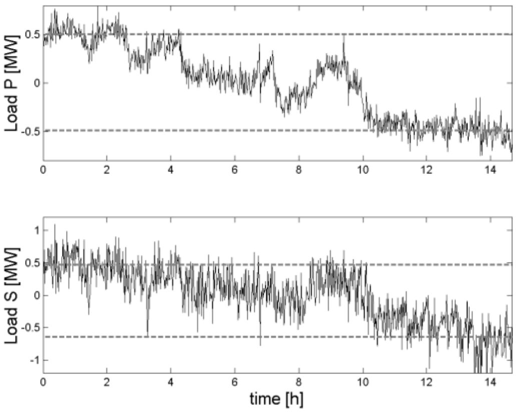

Fig 9. Time series for the refiner motor loads during a test period. The dashed lines indicate mean values for the first and last 2 hours.

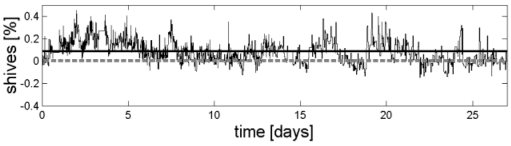

Fig. 10. Shives values for a period of almost a month. The period considered in Figures 5-6 is from the same month. Dashed, grey line: shives mean value from period described in Fig 9. Solid horizontal black line: mean value in this figure.

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

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

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

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 its 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.

Analyzing the control error, i.e. the difference between the setpoint value (SP) and the process value (PV) of the controlled variable (here MFL) using a histogram is one way. In Fig. 11, 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. The control error can be seen as a high-pass filtered signal, which eliminates the effects of trends in the process variables, and it is natural to match an external high-pass filter to find the corresponding cutoff frequency for the system.

One way to find an appropriate cutoff frequency is to minimize the correlation coefficient between the control error and the high-pass filtered process value, Karlström and Eriksson (2013) and this is indeed a simplified way to get a first indication how to set the cut-off frequency. 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 quite good correlation can be extracted for specific cutoff frequencies. In Fig. 12, the correlation coefficients between these two signals are shown versus the ratio of the cutoff frequency and the Nyquist frequency, i.e. ω/ω_n.

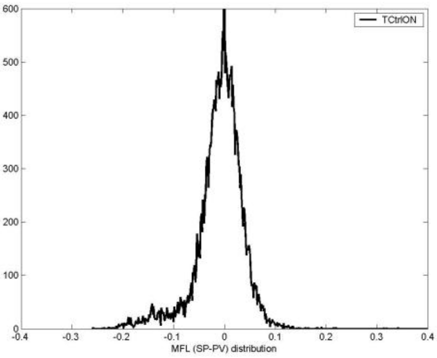

Fig. 11. Control error in terms of a histogram for the entire set of data when running the system in automatic mode.

The obtained high-pass filtered process value, using ω/ω_n=0.025, is shown in Fig. 13 which also seems to be quite good 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.

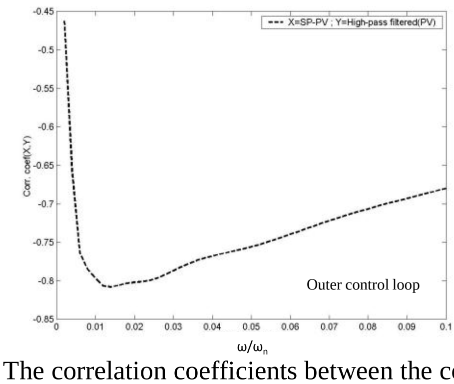

Fig. 12. The correlation coefficients between the control error (SP-PV) and high-pass filtered (PV) for MFL versus the cutoff frequency for a set of samples (sampling rate = 10 minutes).

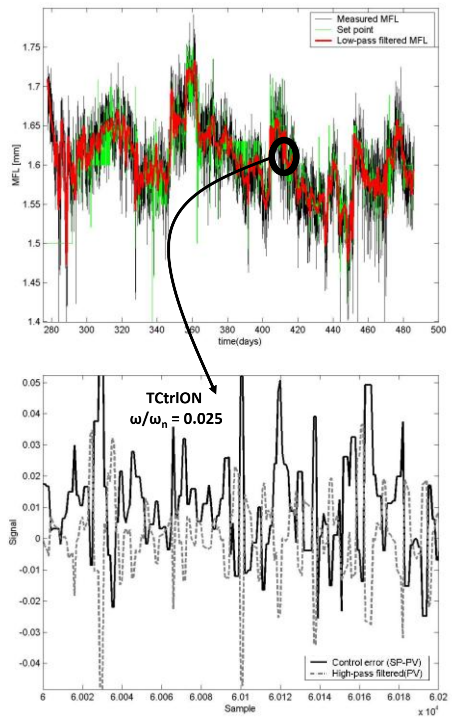

Fig. 13. Upper figure: The set-point and measured value of MFL, and low-pass filtered MFL versus time. Lower figure: The control error and the high-pass filtered process value.

In Fig. 14, 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.

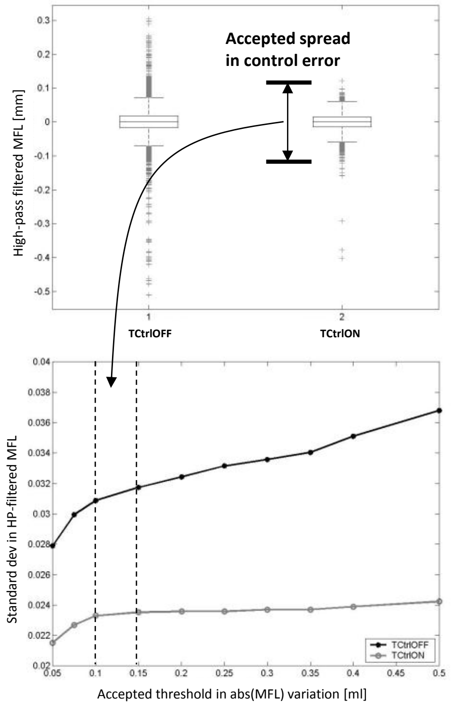

Fig. 14. Upper figure: Box plot for the high-pass filtered MFL (ω/ω_n=0.0125) according to the data sets TCtrlOFF and TCtrlON, respectively. Lower figure: Standard deviations in the high-pass filtered MFL (ω/ω_n=0.0125) versus accepted threshold for TCtrlOFF and TCtrlON.

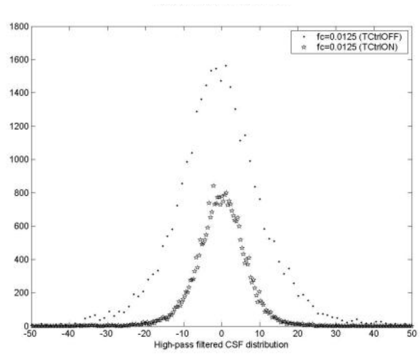

Fig. 15. The distribution in the high-pass filtered CSF for the entire populations TCtrlOFF and TCtrlON shown in Appendix A.

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. 14, i.e. the samples larger than the threshold settings is rejected and not included in the estimation of the standard deviation.

In Fig. 14 it is obvious that the process variations are larger for TCtrlOFF compared with TCtrlON. The accepted interval according to Fig. 11 is 0.1-0.15 mm is marked in the Fig. 14 as dotted lines and exceeds the whisker settings. However, 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.

When controlling MFL in the outer loop the variation in other pulp properties are reduced as well, for example CSF according to Fig. 15.

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 high, but it is hard to confirm the breakage from large CSF variations. Here, a fairly conservative measure based on the lower and upper whiskers as limits is considered. In Fig. 16, 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. 14 and Fig. 16 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.

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 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 and that 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.

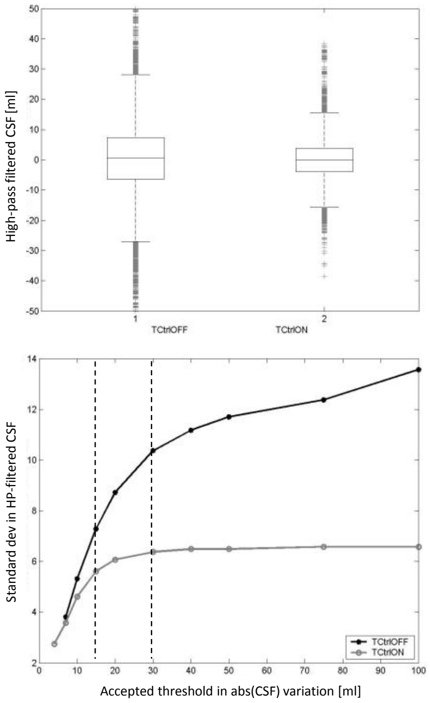

Fig. 16. Upper figure: Box plot for high-pass filtered CSF (ω/ω_n=0.0125). Lower figure: Standard deviations in the high-pass filtered CSF (ω/ω_n=0.0125) versus accepted threshold.

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

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.

4. 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 emphasize 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 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 are 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 at least 50% for the secondary refiner and 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: Without violating specifications in the pulp properties, it is shown that the total power supply to a production line can be reduced at least 2 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. A1.. Note that about 80000 samples, averaged on a 10 minute basis, are covered in the figure, 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. A2. 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.

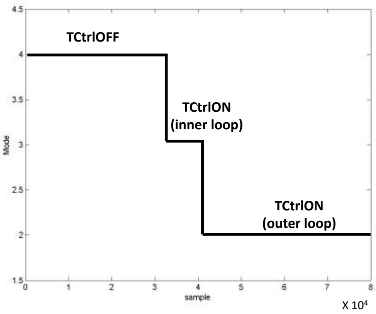

Fig. A1. Periods with three different control modes. TCtrlON has two different modes, that is when just the inner loops are closed, and when both the outer and the inner loops are closed.

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. A2 and Fig. A3. It is even more difficult to foresee the chip mixture impact on the pulp properties in terms of CSF and MFL, see Fig. A4. 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. 6, 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.

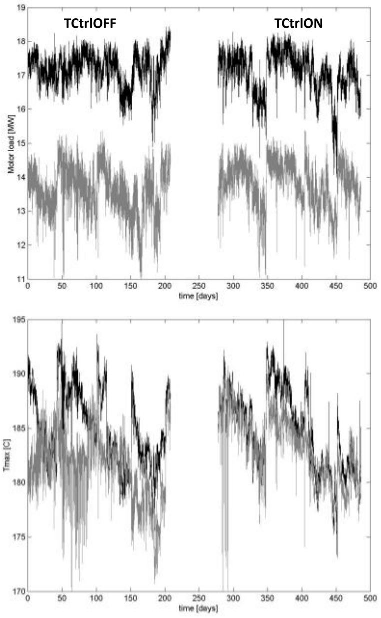

Fig. A2. Motor loads and maximum temperatures for two serially linked refiners versus time when running TCtrlOFF and TCtrlON. Black and grey lines correspond to the primary and secondary refiners, respectively.

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. 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.

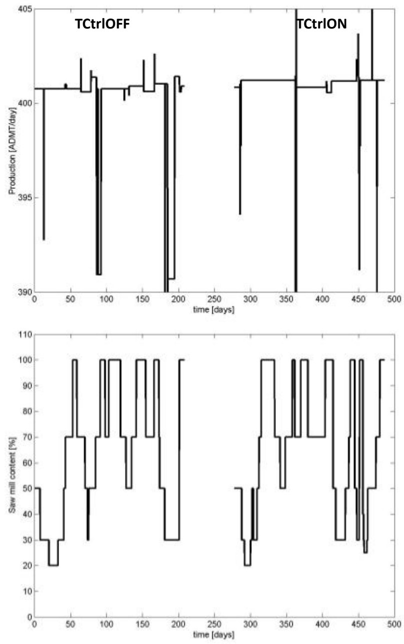

Fig. A3 Production and saw mill chip content versus time when running TCtrlOFF and TCtrlON.

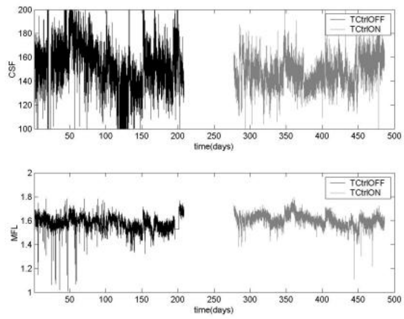

Fig. A4. CSF and MFL versus time when running TCtrlOFF and TCtrlON.

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. B1 and Fig. B2 it can be seen that the stability are significant improved when the new control concept given in this paper is introduced.

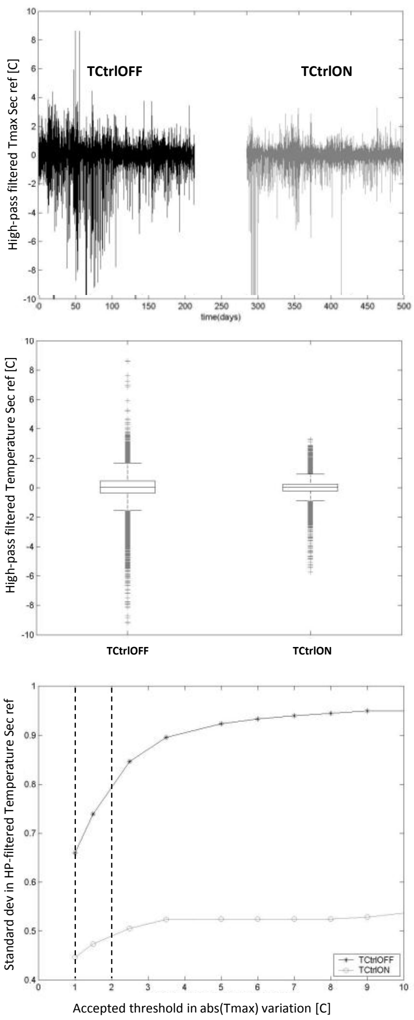

Fig. B1. Upper figure: Maximum temperature in the secondary refiner versus time for the data sets TCtrlOFF and TCtrlON. Middle figure: Box plot for the high-pass filtered T_{max} (ω/ω_n=0.0125) according to the data sets TCtrlOFF and TCtrlON, respectively. Lower figure: Standard deviations in the high-pass filtered T_{max} (ω/ω_n=0.0125) versus accepted threshold for TCtrlOFF and TCtrlON.

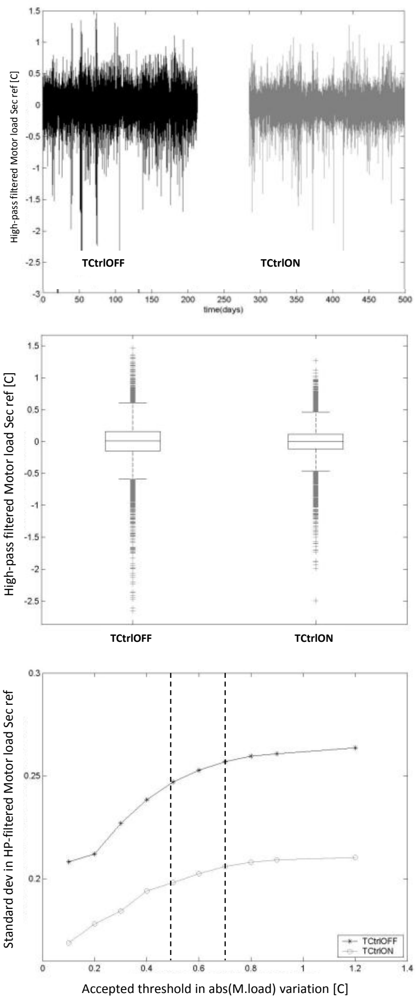

Fig. B2. Upper figure: Motor load in the secondary refiner versus time for the data sets TCtrlOFF and TCtrlON.
Middle figure: Box plot for the high-pass filtered motor load (ω/ω_n=0.0125) according to the data sets TCtrlOFF and TCtrlON, respectively. Lower figure: Standard deviations in the high-pass filtered motor load (ω/ω_n=0.0125) versus accepted threshold for TCtrlOFF and TCtrlON.