

Time Series Analysis of Refining Conditions and Estimated Pulp Properties in a Chemi-thermomechanical Pulp Process

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Frequently sampled process data from a conical disc refiner and infrequently sampled pulp data from a full scale chemi-thermomechanical pulp (CTMP) mill were evaluated to study autocovariance with aspects of potential dynamic modelling applicability. Two trial measurements with an online pulp analyzer at decreased sampling intervals were performed. For variability analysis, time-series containing up to one day of operational data were used. At the chip refiner, the clearest significant autocovariance was identified for the specific electricity consumption, based on the longer sequences. Most of the estimated pulp properties indicated low or non-significant autocovariance, limiting applicability of a specific dynamic model. A mill trial was conducted to investigate the impact from an increase in the conical disc gap on the specific electricity consumption and the resulting freeness. The response time from the gap change in the refiner to measured change in freeness was estimated at 19 min, which was approximately the hydraulic residence time in the latency chest. The relevance of this study lies in applicability of mill-data-driven modelling to capture the dynamics of a specific refining process. Through mill trials the sampling speed of pulp properties was more than doubled to gain insights into short term systematic variations by applying time-series-analysis.

Keywords: Chemi-thermomechanical pulp (CTMP); Freeness; Dynamic modelling; conical disc refiner; Specific electricity consumption; Energy efficiency; Autocovariance

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INTRODUCTION

The final multi-layered product in a paperboard mill designed for consumer packaging consists of layers of both chemical and mechanical pulps, each with different properties to generate the required functionalities. A crucial step in the pulping process is to separate the fibers from each other. For chemi-thermomechanical pulp (CTMP), mechanical loading is applied to the pretreated wood chips. During the process, a small part of the mechanical energy is used for the fiber separation process and a bigger part is converted to heat in the form of vaporized water. The variations in the refiner power and specific energy are important for both the energy and quality performance of the process.

The specific energy and refining intensity are variables that have a major effect on freeness (Qian 1997). This relationship, between the refining conditions and the freeness specifically, is one of the major aspects of this study, and the goal is to increase the understanding of the relationships between the refining conditions and the response (freeness primarily) of the process.

According to TAPPI T227 om-17 (2017), the freeness of pulp is a measure of the rate at which a dilute suspension of pulp may be drained, and to measure freeness, the pulp is diluted to a specific consistency.

Process Description

The refining process converts wood chips into pulp and generates pulp properties suitable for paperboard manufacture. Wood chips are transported from raw material suppliers as well as locally generated from logs at the mill site. After washing and pre-steaming, the chips are chemically impregnated with sodium hydroxide, sodium bisulphite, and a chelating agent prior to preheating at elevated pressure. The chemical pretreatment, in combination with elevated temperature, softens the lignin and improves the separation process of the fibres during the mechanical treatment in the refiner. The refining involves large-scale amounts of energy being transmitted from the rotation of the disc to the chips to develop the requested CTMP properties.

The refiner power and the fiber quality are functions of plate separation, stock feed rate, stock consistency, rotational speed of refiner, and type of input stock (Zand and Wu 1984). The specific refiner in this study was a conical disc (CD) refiner of type RGP-82CD (Valmet, Gothenburg, Sweden) and is described in Fig. 1.

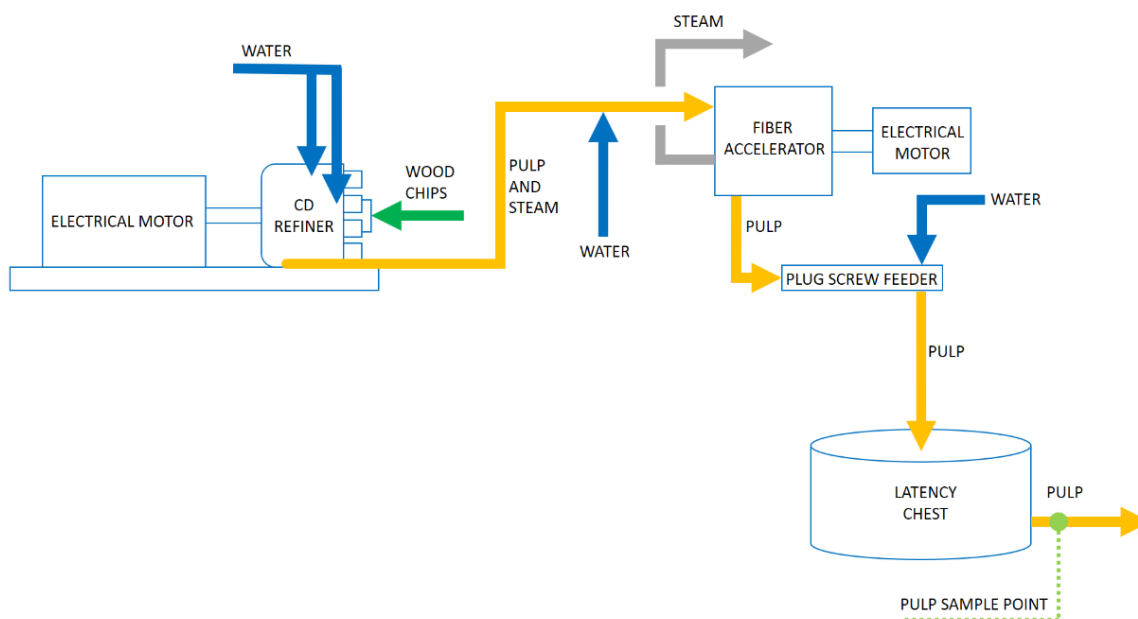


Fig. 1. Simplified process flow chart from the CD refiner to latency chest

The chip flow close to the refiner passed a preheater and screw feeders prior to entry into the refiner. Fibers were refined in a flat zone and a conical disc zone, both with intake for dilution water. After the refiner, the pulp was routed through a blow line at a dry content at approximately just below 50%, then it was diluted with water and entered a cyclone, driven by an electrical motor that separated the steam from the pulp before the pulp entered the latency chest, which had a function of latency removal. Prior to the entry into the latency chest the pulp passed a plug screw feeder that had a water intake that further diluted the pulp, giving a dry content at approximately 6% to 7% in the latency chest. Fibers in wood are originally straight but become deformed during mechanical pulping. The deformation and flocculation results in latency, which is removed when the pulp is

deflocculated by agitation, developing fiber straightening (Gao *et al.* 2013). The specific process studied in this paper involved multiple sensors that continuously collected data that were distributed to the dispersed control system. One of the chip screws prior to the refiner had a gauge for measuring the rotational speed. The process data system had an algorithm that used this signal multiplied with a constant to calculate the production (in ton per hour) of the process. The system also measured temperatures, plate gaps, and pressure at the refiner, in addition to the flow and temperature of the dilution water at both the flat zone and the CD zone. The power of the electrical motor connected to the refiner and the specific electricity consumption (SEC; in kWh/t) were also monitored in the process data system.

One of the challenges in controlling the CTMP process is the difference in retention time between the refiner and the subsequent latency removal that takes place in the latency chest. Inside the refiner, the residence time of the fibers was short and afterwards the pulp was separated from the steam in the cyclone and stored inside the latency chest for a relatively long time compared to the residence time in the refiner. For reference, during normal thermomechanical pulp (TMP) conditions, the residence time at the refining zone can be approximately 0.5 s and approximately 3 s from the ribbon screw to the blow valve (Murton and Duffy 2005). For the latency chest that was studied in this paper, the hydraulic residence time (chest volume divided by volumetric flow) was estimated at approximately 22 min, during the trial measurement. A simplified process flow chart is given in Fig. 1.

Because the pulp properties were measured after the latency chest at the sample point (Fig. 1), this meant that there was a time delay from when the refiner conditions were changed until the change could be measured from the pulp properties. There were also noticeable differences between how often the refining variables and pulp properties were measured. Pulp properties were measured infrequently with non-uniform time intervals, and the refining variables were measured more frequently with uniform time intervals. These characteristics were exemplified for the refiner power and freeness in Fig. 2.

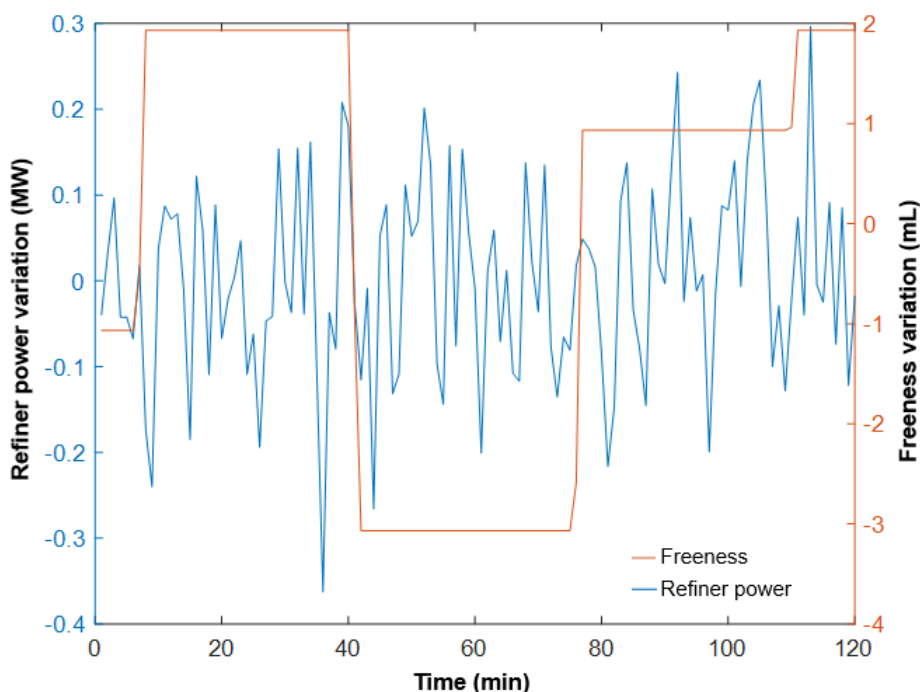


Fig. 2. Characteristics of refiner and pulp measurements

To construct a model of the refining process, the relevant variables of both the process and the pulp need to be readily available. Some of the variables are measured and at some positions they are not. The main variables affecting the pulp properties of the specific process are plate gap, production (feed rate), and dilution water flow. Freeness was the pulp quality variable that was most focused on. Additionally, there are inputs that affect the process by being disturbances that are not measured. Examples of these are chip inlet dry content, chip size distribution, and chip age. The raw material can also contribute variability in terms of aspect of species, contaminants, density, and bark contents. Continuous mechanical wear of the refiner discs (affecting the mechanical defibration) leads to need for disc exchange on recurrent basis. These aspects increase the level of complexity in developing statistical models based on process data.

Previous studies on mechanical pulp modelling

There are several studies of different modelling techniques for the TMP and CTMP processes that address the possibilities and challenges. A general aspect considered when reading the literature is the influence of the specific process design on the results. The response in pulp properties is dependent on, for example, the specific refiner design, process equipment design, and raw material properties. One issue that has been addressed in previous research is the time delay of the freeness response.

To address the time delay, Zhou *et al.* (2016) studied a modelling strategy involving an Auto Regressive Moving Average (ARMA) model to make an online estimation of freeness. The accuracy and capability of the developed model was compared to alternative models in the study and outperformed them.

Tervaskanto *et al.* (2009) modelled the pulp properties of a CTMP refining process and compared the results with an online pulp quality analyzer. The study included a nonlinear static modelling approach for freeness, and one of the objectives with the model was to address the time delay of the freeness measurements after the latency chest; the idea with the model was to avoid waiting for actual freeness measurements. The input to the steady state freeness model was the specific electricity consumption and the refining intensity.

The specific chip refining process in this study had positions where information of the pulp properties would be beneficial for use within process control but, due to practical reasons, hardware sensors were unavailable or unsuitable. If this scenario is present, a soft sensor can potentially be used to calculate quantities based on interaction from multiple signals. Zhang *et al.* (2016) developed a soft sensor for estimating freeness and outlet consistency according to a case-based reasoning method based on operating conditions and pulp quality data. One of the conclusions in the study was that real-time soft sensors estimating freeness and outlet consistency can support reducing the electricity consumption and maintain uniform pulp quality.

Qian (1997) applied mathematical models for several unit operations in the CTMP process and also studied the variability of the chip properties. The case study in the thesis was a production line in a CTMP plant, and the dynamical assessment was conducted in a simulator. For the refiner model, Qian used hydraulic load (applied to refiner plates), transfer screw feeder speed, and dilution water mass flow rate as the primary variables. The model also included multiple secondary variables and disturbances. Freeness, long fiber fraction, and shive content were used to characterize the pulp quality. The simulations showed that the freeness was not affected by small variations in consistency. Models of the CTMP plant were used to study the dynamics of the process by simulating a change in the

properties of the chip and the resulting change in the pulp properties. The resulting time from when a change in the refiner took place until the effect could be seen at the screen room was 1 h, and the time for the process to enter a new steady state was 4 h.

Modelling approaches for describing critical refining limitations have been compared by Eriksson and Karlstrom (2009). The first approach described the used force distribution of the axial thrust and the steam pressure inside the refiner to describe the limitations, and the second approach was based on a dynamic first-principles model, which means that the model is capturing time-varying phenomena and is based on first order linear differential equation. Assuming the steam at the refiner zone is saturated, temperature sensors could be used to describe the pressure profile. The aforementioned work showed that the process had nonlinear properties. The models were based on a number of assumptions in need of experimental verification.

Broderick *et al.* (1997) studied the relationships between the refining conditions and process performance in regards to energy efficiency and pulp quality from a series of pilot trials in atmospheric refining. The paper described how statistical models of refiner performance were generated from the experimental results. Multiple regression analysis was used to construct polynomial models of handsheet quality and SEC. The models were assembled from the process variables and the process response. The results showed that a specific operating window of the plate gap and consistency led to improvements regarding energy efficiency and pulp quality and that the models could be used for studying the ratio of specific energy use for different process steps.

Aim of this study

In this study, process data and pulp measurements from an industrial high consistency refining system were collected during measurement trials with decreased sampling intervals. From discussions with mill staff, freeness variations at high production was identified as crucial to resource efficiency.

The main aim of this paper was the study of autocovariance with aspects of potential dynamic modelling applicability. The objectives are the following: 1) Evaluate autocovariance for a range of refiner variables and estimated pulp properties to study the applicability of dynamic models for pulp property prediction; 2) Explore the hypothesis that pulp residence time in latency chest can be observed in the autocovariance for estimated pulp properties and correlated to the calculated hydraulic residence time; 3) Test the null hypothesis that freeness is constant; and 4) Measure the response on SEC and pulp properties from a change in the CD gap.

The significance of this study lies in applicability of mill-data-driven modelling to capture the dynamics of a specific refining process. Through mill trials the sampling speed of pulp properties was more than doubled to gain insights into short term systematic variations by applying time-series-analysis.

METHODOLOGY

Estimate of Thermal Time Constant for Refiner

Thermal time constants can be used to characterize how an object is heated or cooled. The thermal time constant for the refiner excluding the motor cooling (the cooling flow was not measured) was roughly estimated.

A simple and approximate method for studying the temperature transient of an object is called the lumped heat capacity method. It is assumed that the temperature of the whole object changes uniformly with time and that the temperature is constant at any point within and on the surface of the object at any given instant of time (Lewis *et al.* 2004). The heat transfer between the object and ambient temperature is proportional to the temperature difference between the object and the environment.

If defining an object where V is the volume, ρ is the density, and c_p is the specific heat this can be formulated into,

$$-\rho c_p V \frac{dT}{dt} = hA(T(t) - T_a) \quad (1)$$

(Lewis *et al.* 2004), where h (W/m²K) is the heat transfer coefficient, A is the surface area (m²), t is time (sec), $T(t)$ is the instantaneous temperature (°C) of the object (at time t), and T_a is the temperature of the ambient. This expression leads to a quantity referred to as the time constant of the system τ and is given by:

$$\tau = \frac{\rho c_p V}{hA} \quad (2)$$

Trial Measurements with Decreased Sampling Interval of Pulp Properties

Because the sampling interval of the measurements at the mill was noticeably higher for the pulp properties compared to the refiner process data (Fig. 2), two measurement trials were performed, including online measurements and manual freeness samples that were extracted every 10 min subsequent to the latency chest. The freeness, fiber length, shive-sum, and fines share were collected from the pulp measurements. During normal production, the pulp analyzer samples approximately 2 to 3 times per hour. The reasons for the delay between consecutive samples were the measurement process itself and the use of the online device for analyzing the pulp samples from multiple positions in the process. By reducing the number of positions to one (the sample point after the latency chest, see Fig. 1) for two limited time periods, the sampling interval was decreased, and these measurements were used for the analysis.

One of these trial measurements involved studying the process at stationary conditions. The other trial measurement studied the impact from a change in the CD gap during the trial on the SEC and pulp properties.

Refiner Process Data Analysis

The process data from the specific refiner were plate gap, dilution water flow, specific electricity consumption, and refining temperature. Data were extracted for process sequences reaching up to approximately one day in length.

Interpolation of Pulp Properties

The measurements from the online pulp analyzer were semi-continuous and had varying sampling intervals between each sample. During the measurement trials with decreased sampling intervals, the sampling intervals varied between approximately 6 and 8 min. To calculate the autocovariance, the data needed to have a constant sampling interval, *i.e.*, equal time between each measurement. Thus, the measurements were linearly interpolated, and the resulting pulp property estimate was extracted using a sampling interval equal to the average time between the online measurements.

Repeatability Test of Pulp Analyzer

When studying the process response (in this case the pulp properties) it is important to consider uncertainty in the measurement system. To estimate the repeatability, a batch of CTMP was manually extracted from the process and measured 10 times in the pulp analyzer. The resulting pulp properties were calculated to determine the freeness variations in terms of one standard deviation. The estimated standard deviation in freeness was subsequently compared to the instrument's supplier data and the standard for freeness of pulp (TAPPI T227 om-17 (2017)).

Autocovariance Analysis

Autocovariance analysis is a mathematical method to identify periodicities and other systematic variations in data and the autocovariance function calculates the covariance of the signal with itself at certain lags. The definition involves a term labelled lag (shown as k in Eq. 3), which is defined as the amount of time the data have been shifted. The definition is shown in Eq. 3 (Jakobsson 2013) and the variables are shown in Table 1:

$$R_{xx}[k] = \frac{1}{N-k} \sum_{t=k+1}^N (y_t - \hat{m}_y)(y_{t-k} - \hat{m}_y) \quad (3)$$

Table 1. Definitions of the Variables in the Autocovariance Calculations

Variable	Definition
$R_{xx}[k]$	Autocovariance
N	Number of data points
k	Lag
t	Index of data point
y	Measured variable
\hat{m}_y	Estimation of sample mean

The autocovariance in this study was calculated for lags up to $N/4$, according to a practical rule of thumb described by Jakobsson (2013), and all data were detrended prior to the calculation of autocovariance.

Estimated Confidence Interval

The result plots of autocovariance included 95% approximate confidence intervals as a support when visually identifying significant autocovariances (Jakobsson 2013). For autocovariance, the confidence interval was calculated for a white Gaussian signal with a variance equal to the variance of the detrended time series investigated. In case only a few of the experimentally determined autocovariances fell outside the estimated confidence interval, it could not be ruled out that the detrended experimental time series behaved as a white Gaussian signal.

RESULTS AND DISCUSSION

Analysis of SEC

The SEC generated different indications of autocovariance depending on the length of the sequence. The sequence length of approximately 20 h of process data showed significant levels for time lags shorter than approximately 150 min (Fig. 3) with some

periodical pattern. The 100-min-long process sequence revealed significant levels up to 1 min (Fig. 4) and the shorter (Fig. 5 corresponding to 20 min of measurements, sampled every 1 min) revealed no significant levels. The residence time in the refiner was short. Thus, it was reasonable that no (or very limited) autocovariances existed for lag times of a few minutes. The long-term autocovariances for SEC were likely induced by variations in the incoming chips, potentially caused for instance by variations in species or in the pre-treatment process.

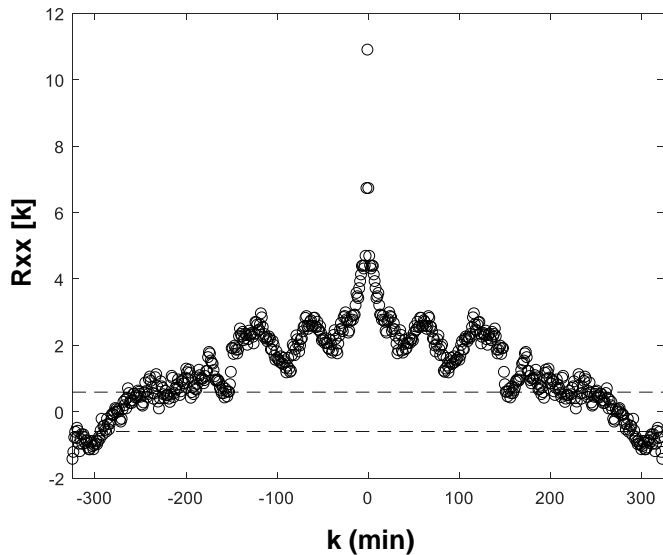


Fig. 3. Autocovariance for SEC originating from approximately 1 day of process data ($k = 1$ min)

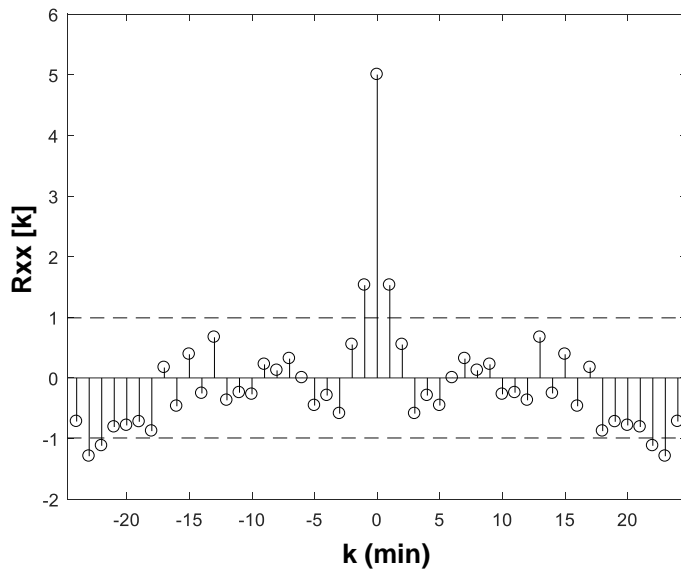


Fig. 4. Autocovariance for SEC originating from 100 min of process data ($k = 1$ min)

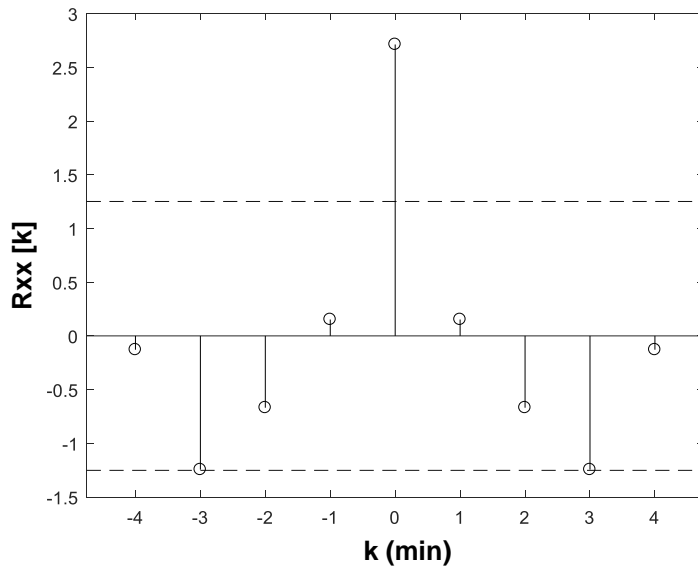


Fig. 5. Autocovariance for SEC originating from 20 min of process data ($k = 1$ min)

Analysis of Refining Temperature, Dilution Water, and Plate Gap

The temperature interval in the CD refiner during the first trial at the mill was 170.2 to 171.4 °C in the CD-zone, and 176.0 to 177.2 °C in the flat zone. Refiner housing had a mean pressure of 453.6 kPa. Refining temperature in the CD zone showed significant autocovariances up to approximately 120 min (Fig. 6), depending on the sample sequence. The 20-min-long process sequence indicated no significant levels.

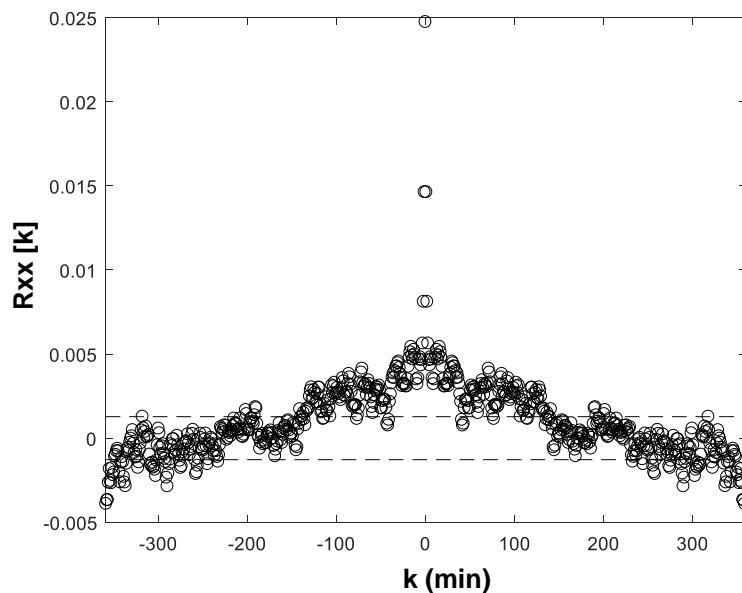


Fig. 6. Autocovariance for refining temperature in the CD zone originating from approximately 1 day of measurements ($k = 1$ min)

Dilution water flow analysis resulted in a low amount of autocovariance. Process sequences in the range of 100 min to approximately one day showed 0 to 2 min of significant estimates and the 20-min sequence showed 0 to 1 min.

The plate gap in the flat zone indicated similar characteristics to dilution water. The plate gap in the CD zone also showed minimal autocovariance, except for the long process sequence, where a somewhat higher level was indicated at up to 20 min.

Regarding the thermal time constant for the refiner, the assumptions in Table 2 and the assumption that at a given time the heat transfer from the refiner to the ambient temperature was proportional to the difference in temperature between the refiner and its surroundings were used as a basis for the estimate.

Table 2. Definition of Assumed Refiner Variables

Variable	Definition	Assumed Value	Unit
C_p	Specific heat capacity	500	J/kg/K
δ	Density	8000	kg/m ³
h	Heat transfer coefficient	20	W/m ² /K
V	Material volume	0.25	m ³
A	Area	4	m ²

The results were calculated based on Eq. 2 and indicated a time constant estimate at approximate 208 min, which was somewhat close to autocovariance results illustrated in Fig. 6. However, it should be noted that this value would be lower if the motor cooling (that was present in the specific refiner installation) was included.

Repeatability tests

The 10-sample repeatability test of freeness in the pulp analyzer was estimated with one standard deviation of approximately 4 mL, which was lower than expected. The analyzer equipment documentation at the mill included no information for the pulp at the specific sample point used in this study but showed one standard deviation (based on 10 samples) of approximately 9 mL for pulp sampled downstream of the process (accept pulp). In TAPPI T227 om-17 (2017), no repeatability values for CTMP at the specific freeness level were found (softwood chemical pulp with a freeness of 600 mL was reported to have a repeatability of freeness of 12 mL). TAPPI T227 om-17 (2017) states that the precision of the freeness test is dependent upon the level of the test and type of pulp being tested, and that softwood chemical pulp (long-fibered pulp) shows more variation than hardwood given standard test conditions.

The repeatability of some of the refiner measurements was unknown, meaning that the standard deviation for the measurement system of the plate gap, dilution water flow, and temperature were not determined.

Trial measurement with decreased sampling interval of pulp analyzer

The average time between the consecutive samples in the online device during the two trial measurements was approximately 8 min and the interpolation of freeness (and fiber length, shive sum, and fines share) was set to 8 min. During the trial the refiner power had low variability, exhibiting a variation of approximately 1%. Because the refiner power had this low variability, it was unlikely to observe any noticeable changes in freeness. For a specific refiner, a change in specific electricity consumption of 6% did not produce a

change in freeness (Sikter *et al.* 2008). This indicated that the variations in specific electricity consumption observed during the measurement trials in this study cannot be expected to produce pulp with noticeable variations in freeness and correspond well with the observation that the variations in freeness observed are within the measurement uncertainty of the online pulp measurement system. This can be observed in Fig. 7, illustrating that freeness had no significant autocovariance during the trial. Equal results were observed for freeness manually extracted and for most of the other pulp properties estimated from the pulp analyzer data. Fiber length and fines share have been exemplified in Figs. 8 and 9, respectively.

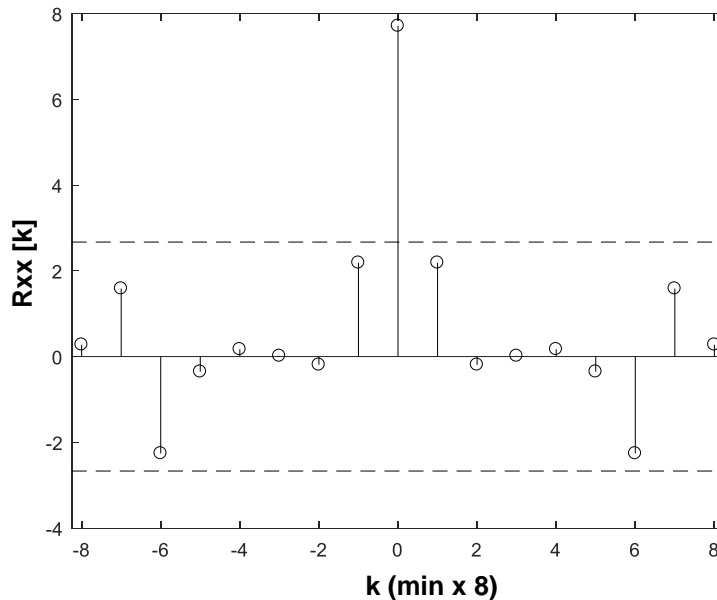


Fig. 7. Autocovariance for estimated freeness ($k = 8$ min)

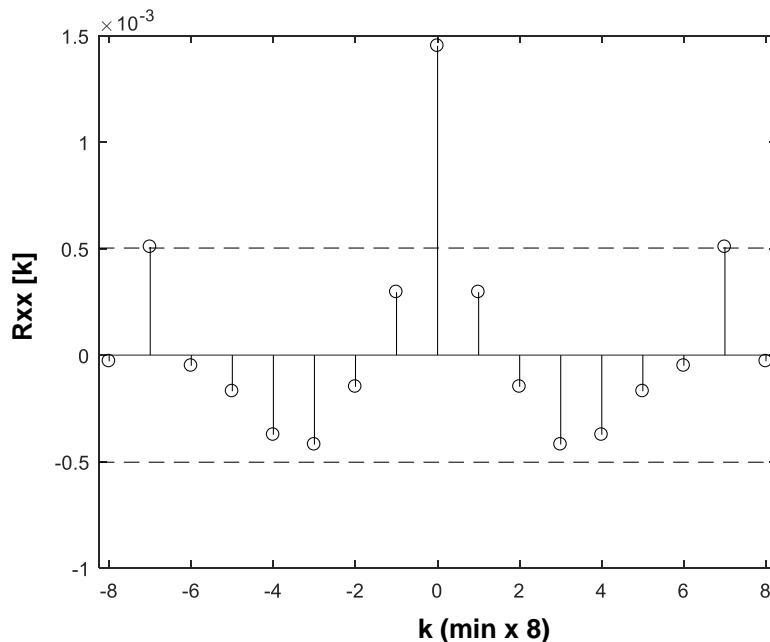


Fig. 8. Autocovariance for estimated fiber length ($k = 8$ min)

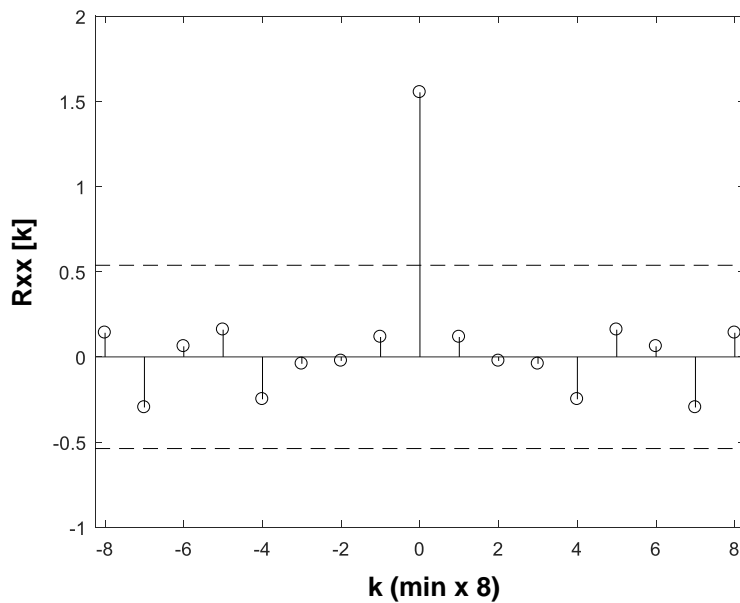


Fig. 9. Autocovariance for estimated fines share ($k = 8$ min)

Manual freeness samples (extracted every 10 min for 4 h and measured in laboratory conditions), showed no significant autocovariance (Fig. 10).

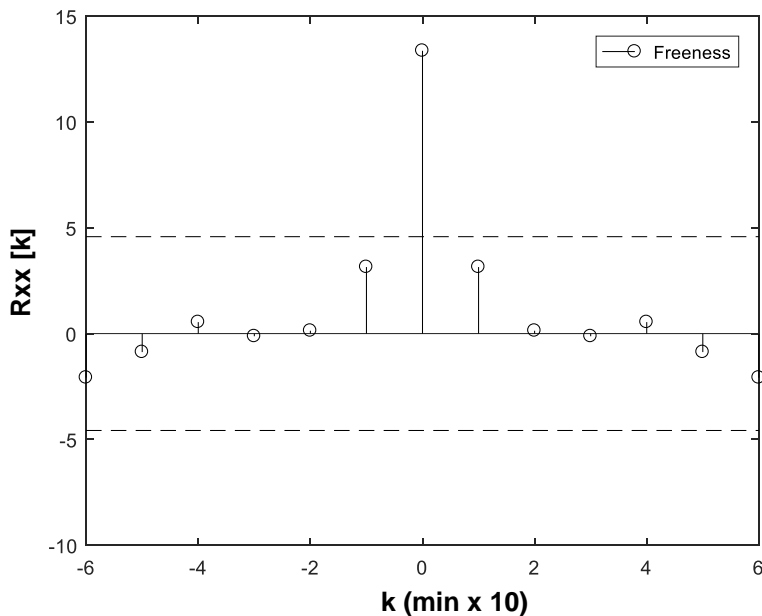


Fig. 10. Autocovariance for manual freeness samples measured at laboratory ($k = 10$ min)

Estimated pulp properties, such as freeness and fiber length, indicated non-significant autocovariance estimates. Most of the resulting autocovariances had characteristics that implied that detrending was a sufficient pre-processing of the data, and differencing was hence not implemented.

To perform the autocovariance analysis of the pulp properties that had an unequal sampling interval, the data needed to be pre-processed with linear interpolation to estimate

values at a constant sampling interval. This procedure resulted in estimated values used as input to the autocovariance, but the potential bias from the linear interpolation was not studied.

An important aspect of the measurement data is the repeatability of the measurement system. For the online device the standard deviations were estimated for freeness. The freeness data that were sampled during the trials were to a high degree within the uncertainty of the measurement system. The portion of freeness data within ± 1 standard deviation was 80%, and for ± 2 standard deviation it was 100%. Thus, the variations in freeness during the trials were not significant because all variations could be explained by the measurement uncertainty of the online pulp measurement system alone. During normal production, the CTMP pulp produced has an even quality with small variations. This also meant that the variations in the pulp quality were not suitable for characterizing the degree of mixing and residence time of the latency chest.

The mill trial with an increased CD gap aimed to study the impact from the gap change on the SEC and pulp properties measured at decreased sampling intervals in the pulp analyzer. The CD gap was increased by approximately 0.1 mm, which resulted in an indication of an increased freeness level. Referring to Fig. 11, the estimated response time was approximately 19 min. This result somewhat mimicked the hydraulic residence time in the latency chest, which was calculated to 22 min at a specific process sequence. The sudden reduction in freeness subsequent to the gap increase was more difficult to explain in physical terms, but the likelihood of it originating from noise in the measurement system cannot be neglected.

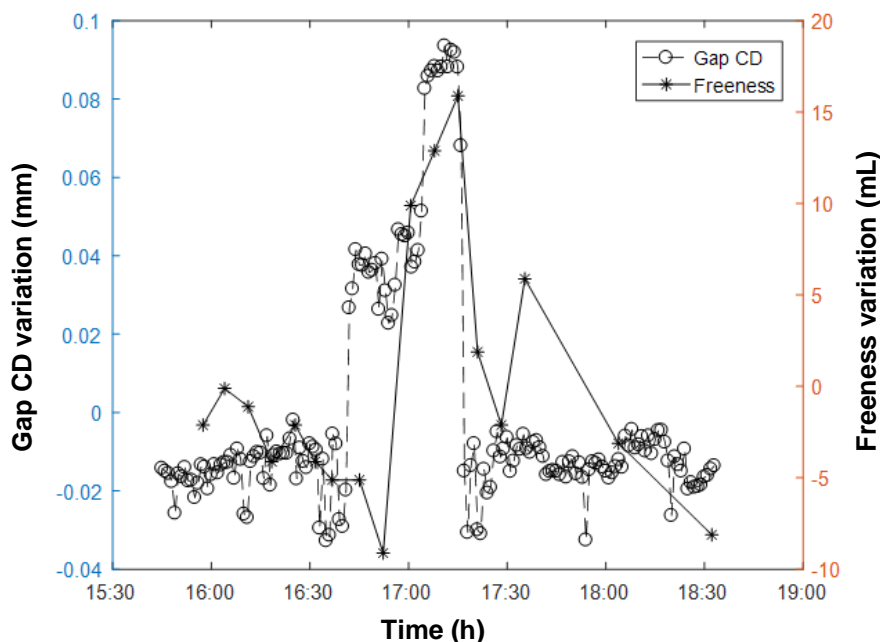


Fig. 11. The CD plate gap and freeness measurements from trial

The CD plate gap was increased in two steps of each 0.05 mm, and the reduction in the SEC was indicated at less than 10 kWh/t (Fig. 12).

Referring to the described objectives (1 to 4) of this study, the corresponding results indicated that objective 1) for the majority of the studied time series that were based on specific process data, pulp quality autocovariance was not significant enough for successful

prediction of pulp quality by dynamic modelling; 2) The hypothesis was rejected because the residence time in the latency chest was not observed in the autocovariance estimate; 3) The null hypothesis could not be rejected with the aspect of the variability of the observations; and 4) The gap step-change generated a feasible response time estimate at approximately 19 min.

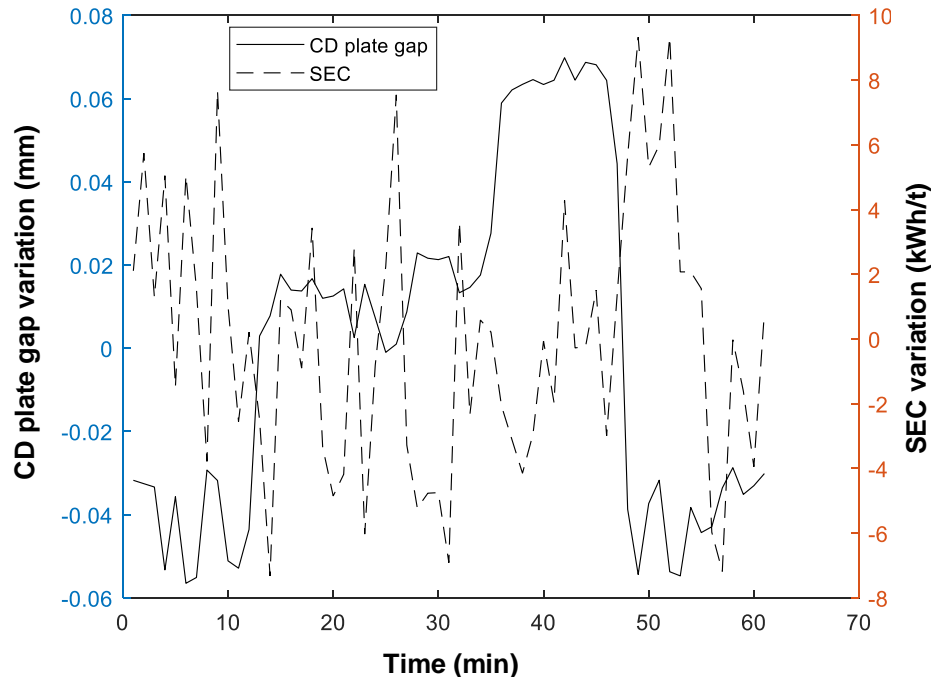


Fig. 12. The CD plate gap and SEC from trial

It shall be noted that the interpolated estimates of the pulp properties were required due to the fact that the method used in this study required constant time between each sample. However, the estimating procedure might cause potential error, and a study of the potential influence of this appears relevant for future work.

CONCLUDING REMARKS

Most of the estimated pulp properties indicated low or insignificant autocovariance (calculated for several lags) because the observations were within the measurement uncertainty of the online pulp measurement system. The autocovariance analysis indicated that several refining and pulp variables had characteristics similar to a white Gaussian signal. Furthermore, any observed variations in the specific electricity consumption during the trial measurement were so small that they could not be expected to result in substantial variations in the pulp quality. These two observations jointly led to the conclusion that during nearly stationary operation of the CTMP process, any variations in the pulp quality were so small that they could not be decreased using the present measurement system for identifying them.

ACKNOWLEDGEMENTS

This study involved personnel from multiple organizations. The measurements and the research were accomplished in collaboration with the mill, R&D organization, Karlstad University, and the measurement systems suppliers. Maria Björk and Rickard Wadsborn were company supervisors, and the Technology Development team at Stora Enso was involved in constructive discussions. Robert Westberg, Ann Lundqvist, Anders Waller, Sven-Erik Thyberg, and the production operators were helpful at the mill. Tomas Storsjö contributed with technical support regarding extraction of measurement data from the pulp analyzer. Ola Johansson was involved in a measurement trial at the mill. The authors would like to express appreciation for the valuable support of the contributors. The study was performed as part of the Industrial Graduate School VIPP (Values Created in Fiber-Based Processes and Products) at Karlstad University, with the financial support of the Knowledge Foundation, Sweden, and by Stora Enso.

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Article submitted: November 20, 2018; Peer review completed: April 20, 2019; Revised version received and accepted: May 14, 2019; Published: May 24, 2019.
DOI: 10.15376/biores.14.3.5451-5466