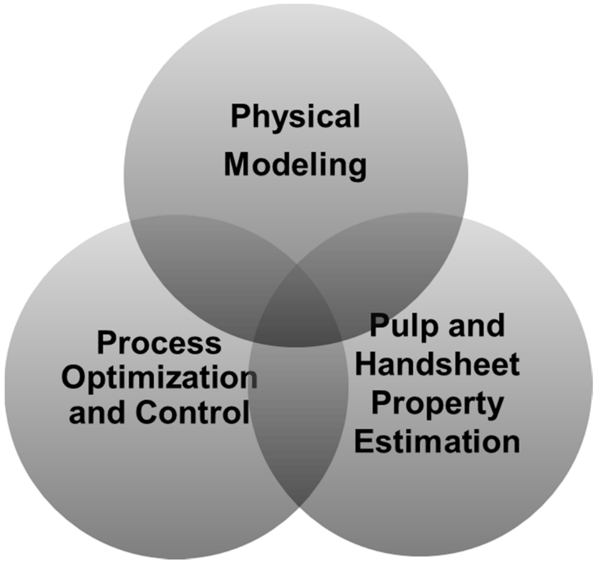
Intensified Refining and Optimal Control in Chip Refiners



Introduction

This overview comprises a short summary of the main findings when optimizing refining systems and three different intertwined research areas are analyzed:

- “Physical Modeling”
- “Process Optimization and Control”
- “Pulp and Handsheet Property Estimation”

The primary goal of project has been to show how the refining energy can be reduced by 15 % through better control of the fiber flow in the refining zone. A second goal has been to supply the industry with modeling tools to improve the refining technology, and thus improve the energy efficiency even further.
Primarily, the project has been focused on four issues which must be considered when approaching more energy efficient refining conditions:

- The material transport in the refining zone and how to control for a better throughput, i.e. a higher production;
- The risk of fibre pad breakdown (resulting in excessive fibre shortening or maybe eventually in a plate clash) and how to in particular avoid such irreversible conditions when applying high production rates and/or increased refining intensity;
- The refining bars impact on fibres at different operating conditions, like
    - uneven fibre distribution,
    - pulsation in fibre pad pressure gradients (in both tangential and radial directions) which may demand stabilization and improved process control,
    - change of the fibre pad properties by chemistry, alternative pre-treatment, refining temperature (fibre softening e.g. Thermopulp) or segment design. Here, reversible (steam generation) and irreversible (defibration/fibrillation) will be in focus.

- A smooth chip/fibre feeding system to the refiners and process control.

Summary of results

In short we can conclude that the “Physical Modeling” became a backbone in the research. The algorithms have proven to give robust estimates of several important variables such as consistency, fiber residence time, bar-to-bar force estimation etc. *This makes it possible to implement the algorithms, which also are called the Extended Entropy Model, as a soft sensor package in on-line applications.*

During an extensive long term test, performed during two years, it was possible to show that *without violating specifications in the pulp properties, the total power supply to one 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 (two production lines), probably more as this savings refers to the stabilization of the process. If using the proposed “Process optimization and control concept” to find new operating points the saving potential will be about 350 kWh/ADMT* .

Finally it was shown that a computer based methodology can be introduced for “Pulp and handsheet property estimation”. The test series studied comprised in total 63 TMP and 160 CTMP pulp samples. It was shown that that *an adjusted R^2>0.85 can be reached for all properties which opens for future on-line implementations of pulp and handsheet property estimations as well*.

Physical Modeling

To reach improved energy efficiency, there is a need for increased understanding of how different process conditions in Thermo Mechanical Pulp (TMP) refiners influence the final pulp quality. Energy efficiency can be defined in many ways, see Miles and May (1990) and Kerekes (2011). Ferritius et al. (2014) defined energy efficiency as increased tensile index for a certain energy input in a CD-82 refiner. It was shown very large differences in energy efficiency with respect to tensile index at different operations points. This indicates that reducing electrical consumption in TMP is challenging as pulp quality, which is a complex measure, is often assumed to be affected negatively when reducing the motor load or increasing the production throughput, see e.g. Hill (1993), Berg et al (2003), Dahlqvist (1985), Eriksson (2005), Karlström and Isaksson (2009). In relation to this, increased process knowledge, obtained from measurements in the refining zone, has been requested and proven useful when selecting the set points for the pulp properties. This was early discussed by Härkönen et al. (1999), Rosenqvist et al. (2001), Sikter et al. (2007) and Karlström (2013)) who proposed in-depth studies of the refining zone conditions.

When it comes to modeling of refining zone conditions, the equations developed by Miles and May (1990, 1991) are still taught. That model is nonetheless severely limited by the facts that it is static and that essential variables and parameters, such as plate clearance, bar pattern, temperature and fiber distribution between the refining segments, are not considered from a fluid dynamic perspective. Recognizing that modeling of physical phenomena inside the refining zone is necessary, Huhtanen (2004) used a non-newtonian fluid dynamic approach to overcome some of these problems. However, the computational fluid dynamic (CFD) modeling approach, proposed by Huhtanen (2004), is not focused on changes in the flow characteristics, when e.g. closing the plate gap, which is essential when studying dynamic responses based on process data. However, such CFD-models include the dynamic viscosity as a natural process variable to cope with. Unfortunately, this is not so often mentioned in the literature but Di Ruscio (1993) derived an interesting model for control purposes based on a physical approach where the dynamic viscosity played a central role.

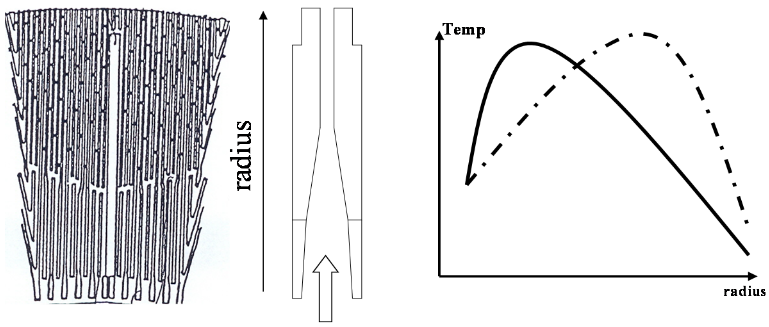
From a modeling perspective it is important that the physical properties are available at different radial position and scales as these variables are dependent on e.g. type of refining segments and actual process conditions. It is also important that the model can handle the energy input (motor load) as a distributed work in the refining zone from a macro-scale perspective. These statements are documented by Karlström et al. (2008), Eriksson (2009) and Karlström (2013) where the spatial measurement of the temperature profile was used for solving the material- and energy balances in the refining zone. These papers formed the basis for a model which later on was called “the entropy model” since both reversible (thermodynamical) and irreversible (defibration/fibrillation) work was handled simultaneously. The model was relatively premature and one of the limitations of this model was related to the plate gap estimation where the pulp viscosity vector was assumed to be known.

The work performed in this project is rather extensive, from a theoretical perspective, and comprises four consecutive papers presenting the development of a comprehensive multi-scale model with focus on fiber energy efficiency in thermo mechanical pulp processes. The fiber energy efficiency is related to the defibration and fibrillation work obtained when the fibers and fiber bundles interact with the refining bars. The fiber energy efficiency differs from the total refining energy efficiency which includes the thermodynamical work as well. It is

shown that extracting the defibration and fibrillation work along the radius in the refining zone gives information valuable for fiber development studies.
Moreover, it is shown that models for this process must handle a large number of physical variables as well as machine specific parameters at different scales.

To span the material and energy balances, spatial measurements from the refining zone must be available. So far, measurements of temperature profile and plate gaps from full-scale Twin-, RTS-, SD- and CD-refiners have been considered as model inputs together with process variables such as motor load, production rate, dilution water, inlet pressure and casing pressure. This makes it possible to derive the distributed work and consistency profile in the refining zone. Some types of refiners like the Twin and CD-refiners an extension must be included as the split of the total work must be handled. In more details; for Twin refiners it means the split between the two parallel zone and for CD-refiners it means the split between the two serially linked flat zone and conical zone. The project address this as a specific topic and the mathematical algorithms, which constitute the Extended Entropy Model, solve the distribution by using some important assumptions see further Karlström and Eriksson (2014a,b). The articles also focus on other important issues like e.g. the design of refining segments and different control concepts. The specific need to understand how the refining segment pattern interact with the fibers is thoroughly penetrated in the last papers in this series (Karlström and Eriksson 2014c,d) which means that the algorithms can take different segment taper and patterns into account see *Fig. 1*.

In short we can conclude that the segment pattern, schematically given in *Fig. 1a*, includes e.g. geometrical information which must be pre-specified to model the bar-to-fiber impact properly in different parts of the refining zone. The true distance between the segments mounted on the rotor holder and the stator holder in *Fig. 1b* is also important to include as it directly affect the shear force distribution obtained between the segments. Large taper results in a larger distance between the two segments in the inner part of the segments see *Fig. 1b*. That forces the temperature maximum outwards the periphery while a narrower taper will force the profile temperature maximum closer to the center of the plates, see *Fig. 1c*. In general, a larger taper is used when running low energy segments which means that the selection of refining segments is important as the refining efficiency and process stabilization are affected considerably for different types of patterns. This will be a focus in the next project called "LESS- Low Energy Strategic Segments".



a b c

Fig. 1: a) A typical section of a segment where the pattern is visualized together with a sensor array for temperature measurements. b) Cross-section of two segments on stator and rotor. The distance between the two segments is a function of radius. c) Temperature profiles for two different tapers. Dash dotted line corresponds to segments with a large taper ("open" segments).The solid line illustrates a segment with a narrower taper.

The taper and refining segment patterns are vital also from another perspective namely when estimating the distributed fiber residence time and other hidden physical variables. The fiber residence time will be commented later on but for the moment we leave that variable and focus on the pulp dynamic viscosity instead. The pulp dynamic viscosity has never been possible to measure on-line in any refiner so far and in CD-refiners for instance, see *Fig. 2*, it is shown that the "Extended Entropy Model" makes it possible to estimate the distributed pulp dynamic viscosity as well. This is an essential result as this vector normally is unknown in refining processes but certainly useful for all fluid dynamic models describing the bar-to-fiber interactions. In future research it is natural to analyze the viscosity in more details when adding chemicals to the process for reduction of energy consumption.

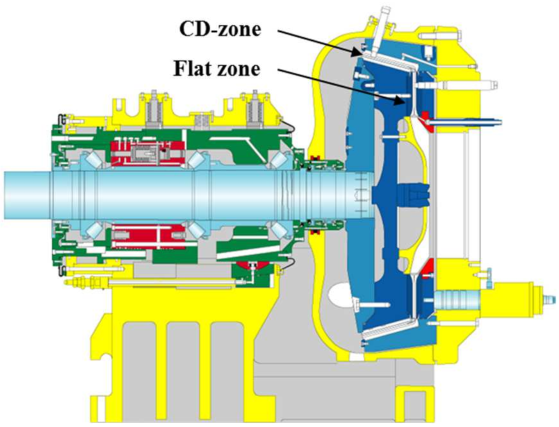


Fig. 2: A schematic drawing of a CD-refiner. The vertical flat zone is directly linked to the conical (CD) zone via an expanding point which is important to consider when modeling the material and energy balances.

The algorithms, which solve all the material and energy balances, are rather extensive and we will not reproducing them in this summary but to some extent it is important to understand that the “Extended Entropy Model” does not only cover the entropy concept. Instead it includes enthalpy balances as well. This is best illustrated in *Fig. 3* and it is important to mention that the block called “Mixing point between FZ & CD” corresponds to the position in the refining zone where dilution water is added to the CD-zone. For simplicity, this block represents the position between the 8th temperature sensor in the flat zone and the 1st temperature sensor in the CD-zone (In several CD-refiners, the dilution water is added distributed over the segments but that is not considered in this overview). As seen in *Fig. 3*, in this position the direction of steam can be both backwards and forward in the refining zone. Normally, the steam is moving forward but in some cases, when the temperature is higher in the inlet of the CD-zone compared with the temperature in the periphery of the flat zone, back-flowing of steam can occur. Similarly in the blocks called “Inlet mixing point”, “the inlet mixing zone” and the “Flat zone…..”, the steam can be evacuated both forward and backwards and additional steam can be added to the first mixing zone to force the steam to flow forward instead of backwards. This knowledge become important when introducing more advanced control concepts and will be considered in the project “LESS- Low Energy Strategic Segments”.

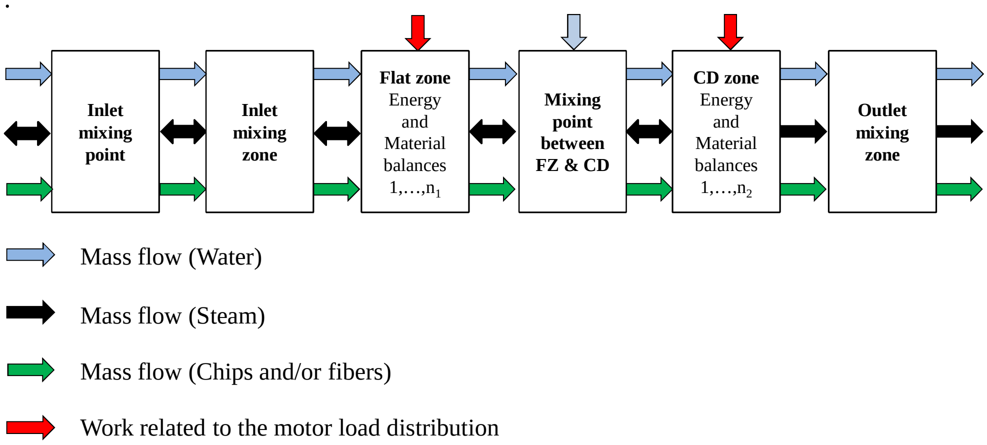


Fig. 3: Schematic description of the material and energy balances spanning the CD-refiner. Note, only two blocks are directly associated with the entropy-concept where the irreversible work is considered. The other blocks comprise mainly material and enthalpy balances.

Process Optimization and Control

Based on a number of articles see Hill et al. (1979), Hill et al. (1993), Johansson et al. (1980), Dahlqvist and Ferrari (1981), Oksum (1983), Honkasalo et al. (1989) it was earlier stated that the specific energy, i.e. the relation between refining energy consumption and the assumed production rate, is not sufficient for the control of complete refiner lines. The reason is that specific energy is an average of the total work distributed along the surface of the refining segment with limited information of the fiber distribution and consequently the local defibration and fibrillation inside the refining zone. Moreover, specific energy as a controlled variable tends to be sensitive for variations in chip feed rate as well as in the chip properties.

Even though using specific energy as a measure and controlled variable is associated with several weaknesses this is still very common in control concepts on the market due to the lack of measurements of physical variables inside the refining zones, see Sikter et al. (2007).

Karlström and Isaksson (2009) introduced the concept of internal states to handle the process description from a control engineering perspective; these are defined as physical properties obtained from measurements (or models) inside the refining zone. As an example; typical internal states are the measured temperature profile, estimated consistency profile and distributed fiber residence time.

At the same time, the external states were defined as measurements obtained from devices outside the refiners, such as motor load, dilution water flow rate, plate gap (or hydraulic pressure), the on-line pulp property analyzers and blow-line consistency sensors etc.

In this report it is conclude that it is important to measure or estimate both internal and external states together with refining segment parameters, as they are used when spanning the material and energy balances in the extended entropy model, see Karlström and Eriksson (2014a,b) and Karlström and Hill (2014a,b) or dependent variables as described below by Karlström et al. (2015a,b,c). Hence, the "extended Entropy Model" can be seen as soft sensor for estimating a number of "hidden" internal states which can be used when decoupling the processes. Normally, all control concepts handle decoupling. In the articles written in this project we are trying to use the internal states to get access to the concept of "Natural decoupling" which is best defined by the following example:

Natural decoupling: The flow pattern in a refiner is complex, with three physical states (chips, water and vapor) to be handled simultaneously. The steam/fibers generated in the refining zone are commonly assumed to be saturated, i.e. the pressure is a function of the temperature and vice versa. Steam is evacuated both forwards and backwards as described above. This means that we have 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. 4*.

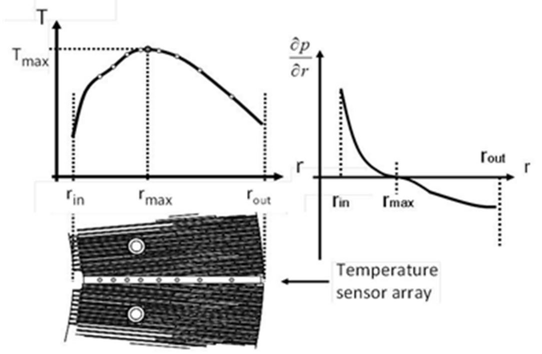


Fig. 4: A typical temperature profile, and corresponding pressure gradient, from a primary refiner where a sensor array is placed between two refining segments. The white dots on the black lines showing the temperature profile indicate the positions of temperature sensors T_1 to T_8.

As outlined by Karlström and Eriksson (2014a,b) it is important to control the maximum temperature as it sets the gradients for the refining zones. If the gradients are varying too much and not controlled, the fiber residence time will be affected and thereby the final pulp properties. It was also shown that the segment pattern will have a strong impact on the control concept chosen. This is unfortunately not considered in traditional refiner control concepts. Other nonlinearities, like refining segment wear also occur and introduce many problems in traditional MPC-control concepts.

However, when the temperature profile is available and thereby the maximum temperature in *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} obtained from a Twin refiner, see *Fig. 5*.

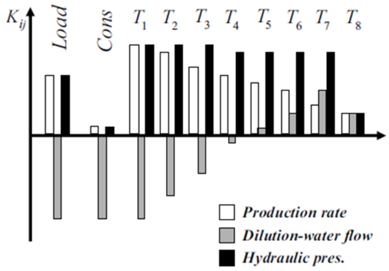


Fig. 5: Low-frequency gains from a primary refiner for different elements in a 10x3- system.

As described, the temperature sensors T_4 and T_5 as process outputs will give small gains from the dilution water feed rate *D*, while the other temperature sensors lead to larger gains.

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 which results in a clear system description useful for control at low maintenance cost. As an example of this statement, consider the complex system matrix describing the dynamics (g_{ij}) for a CD-refiner

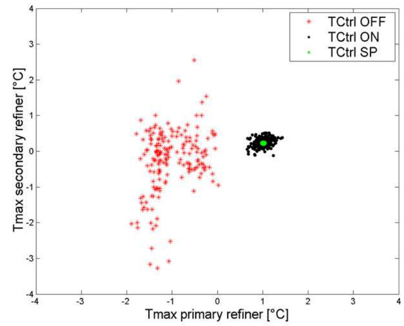
$$y = \begin{bmatrix} T_{\max FZ} \\ C_{FZ} \\ T_{\max CD} \\ C_{CD} \end{bmatrix} = Gu = \begin{bmatrix} g_{11} & g_{12} & g_{13} & g_{14} \\ g_{21} & g_{22} & g_{23} & g_{24} \\ g_{31} & g_{32} & g_{33} & g_{34} \\ g_{41} & g_{42} & g_{43} & g_{44} \end{bmatrix} \begin{bmatrix} S_{FZ} \\ D_{FZ} \\ S_{CD} \\ D_{CD} \end{bmatrix}$$

where the inputs are the plate gap (*S*) and the dilution water (*D*) in the refining zones described by the subscripts FZ and CD, respectively. The maximum temperature (T_{max}) and consistency (*C*) out from each zone are considered as outputs and possible to control. In this project, it is shown that thanks to the natural decoupling the complex system described above become much easier to handle as many of the anti-diagonal elements in the matrix can be neglected, see Karlström and Hill (2014c).

$$y = \begin{bmatrix} T_{\max FZ} \\ C_{FZ} \\ T_{\max CD} \\ C_{CD} \end{bmatrix} = Gu = \begin{bmatrix} g_{11} & & & \\ & g_{22} & & \\ & & g_{33} & \\ & g_{42} & & g_{44} \end{bmatrix} \begin{bmatrix} S_{FZ} \\ D_{FZ} \\ S_{CD} \\ D_{CD} \end{bmatrix}$$

In short, this means that four SISO-loops can be designed if the “Extended Entropy Model” is used for estimating the consistencies C_{FZ} and C_{CD}. The reason why the element g_{42} is included in the system matrix is that the consistency variations in the flat zone affect the consistency dynamics in the CD-zone.

For other types of refiners, like SD-,Twin- and DD-refiners this system become much more simplified. The concept was tested in a full-scale production line with Twin-refiners and in a short term perspective the follow up of the improved control performance is straight forward as seen in *Fig. 6* (TCtrlOFF: Manual control, TCtrlON: Automatic control) 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. 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.



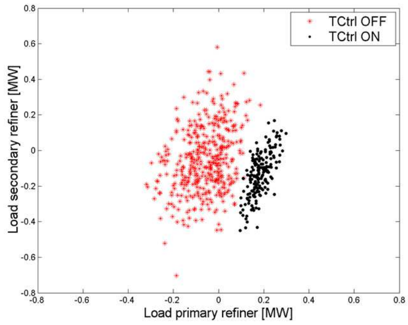


Fig. 6: Upper: T_{max} in secondary refiner vs. T_{max} in primary refiner. Red: TCtrl OFF; black: TCtrl ON; green: set-point for T_{max} during TCtrl ON. Lower: Operating window for the motor loads.

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 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 7*. This temperature reduction corresponded to a significant reduction in the refiner motor loads, as shown in *Fig 8*. In addition to that, other measured pulp properties were analyzed as well. A comparison with shive content over a longer period, *Fig. 9* revealed that the motor load reduction in *Fig 8* could be performed without violating specifications also for longer periods.

In a long term perspective 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. In this project, the process was followed during one year with no control except traditional consistency and motor load control and one year in automatic mode with consistency and maximum temperature control.

It is obvious that 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 and to follow large sets of data a special high-pass filtering technique was introduced, see Karlström et al (2014d).

The cutoff frequency for the controlled variable MFL was chosen according to the obtained control error for a well-tuned cascade control system. It was shown that a good comparison between different data sets can be established using the method. As a consequence of the method chosen, it was shown that the standard deviations in MFL and CSF were reduced about 40-60 % when using the new control concept. Reductions in variations of other pulp properties were 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 was 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.

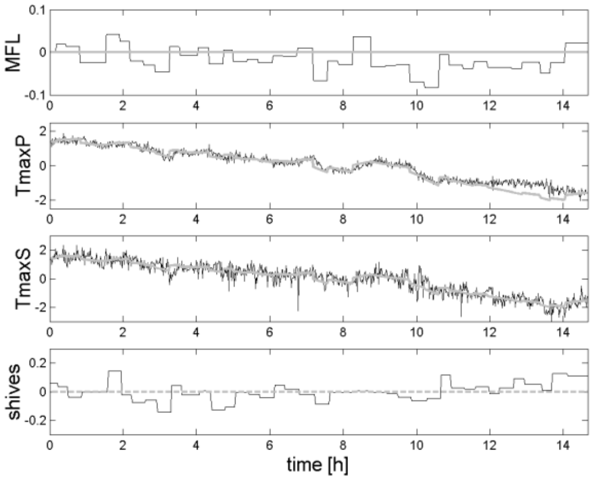


Fig 7: Black lines show present values (measurements), grey solid lines show set-point values and grey dashed line show mean value over the time period. From top to bottom: MFL in mm, T_{max} primary refiner in °C, T_{max} secondary refiner in °C, shives in %.

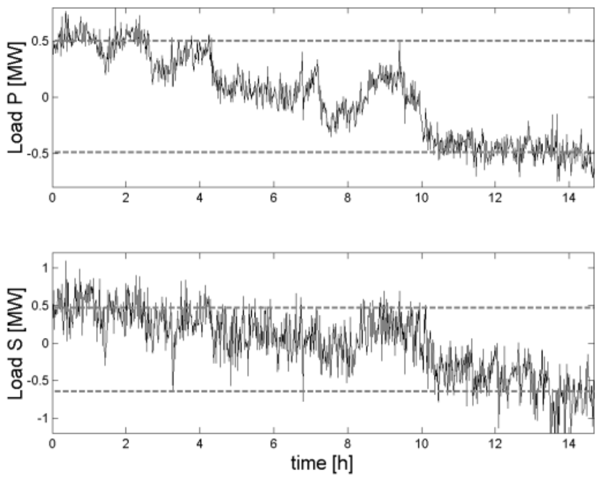


Fig 8: Time series for the refiner motor loads during a test period. The dashed lines indicate mean values for the first and last 2 hours.

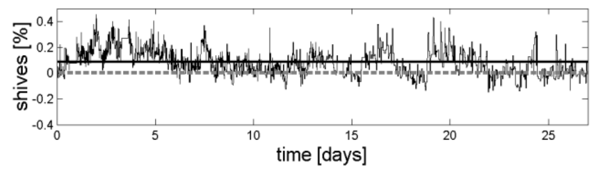


Fig. 9: Shives values for a period of almost a month. The period considered in Figures 5-6 is from the same month. Dashed, grey line: shives mean value from period described in *Fig 8*. Solid horizontal black line: mean value in this figure.

In this follow up it is shown 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 was 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.

It was also concluded that an extensive potential for energy savings, within the windows of accepted pulp properties, exist and 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 with two production lines, probably more as this savings refers to the stabilization of the process. If using the proposed “Process optimization and control concept” to find new operating points the saving potential will be about 350 kWh/ADMT.

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. This corresponds well with the results presented by Jönsson (2011). In an international perspective, the documented emissions are sometimes obtained from coal condense fossil-fuel power plants which means that the estimated emissions are increased to about 20 000 tons per year.

Pulp Property Estimation

When performing test series, process data is normally oversampled and provided at a high sampling rate to fulfil the Nyquist-Shannon sampling theorem to prevent any aliasing, see Nyquist (1928), Shannon (1949) and Jerri (1977). However, when pulp samples are taken from the process for pulp and handsheet property analysis these samples are typically undersampled with non-equidistant sampling intervals. This can be seen as data residing in a much lower dimensional space where important dynamic information is lost for future analysis. To overcome such problems Karlström et al. (2015a), showed how to interlace the undersampled pulp and handsheet properties and ThermoMechanicalPulp (TMP) process data using piece-wise linear functions. The idea was to expand the pulp and handsheet property data to obtain a common time frame for further dynamic analysis in any type of refining system. 63 laboratory samples of tensile index, mean fiber length and Somerville shives content were analyzed based on pulp samples taken in the blow-line. The sampling procedure was carefully designed using several partial samples during a three-minute period where the sampling time was well-documented. It was shown that the temperature profile measurements together with fiber residence time and consistency profiles inside the refining zone (Karlström and Eriksson (2014a,b) are important internal variables when modeling pulp properties (Karlström et al. 2015a). It was confirmed that refiners, which are operating in a large dynamic operating window, are strongly affected by different non-linearities such as process limitations, different raw materials and wear of the refining segments. This has been known for decades and linear regression approaches to model pulp and handsheet properties based on process data sets, often fail even though reliable process conditions are used. This is best illustrated in *Fig. 10*, where the estimated mean fiber length (MFL) from a 1st order polynomial fit is given using the specific energy input as an independent variable (predictor), see Karlström et al. (2015a). Some improvements can be obtained by increasing the polynomial degree, but this is still not good enough as the residual variance from the fitted model is too low (1st order $R^2 \approx 0.3$, 2nd order $R^2 \approx 0.44$, 3rd order $R^2 \approx 0.45$). If performing the same estimation for tensile index and Somerville the following residual variances are obtained: (1st order $R^2 \approx 0.25$, 2nd order $R^2 \approx 0.25$) and (1st order $R^2 \approx 0.65$, 2nd order $R^2 \approx 0.66$) respectively.

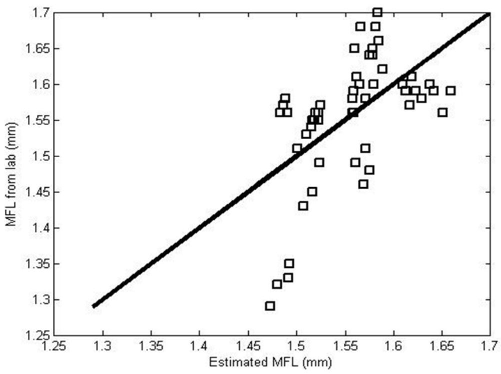


Fig. 10 - Estimated and measured MFL from the 63 pulp samples obtained during a three month period. The straight line corresponds to the optimal fit when using specific energy as a predictor.

So! How can we handle the problems to get reliable pulp and handsheet estimations?

The idea that internal variables can be used as important predictors was only vaguely understood when the project was started. Indications existed but no deeper analysis had been performed concerning the use of the results obtained from the physical modeling efforts. Therefore, the internal variables were verified versus actual process conditions (Karlström and Eriksson (2014a,b,c,d) before introducing them as predictors in the piece-wise linear functions.

To illustrate how to use piece-wise linear functions the tensile index and Somerville are shown versus the time for a typical production level in a full-scale TMP production line, see *Fig. 11*. It is shown that even small fluctuations in the estimated Somerville and tensile index can be captured and compared with the measured tensile index and Somerville (red). In *Fig. 11*, the corresponding mean values of the estimated pulp properties (green) are included as well, see further discussion in Karlström et al. (2015b).

These results strengthened earlier tests in other full-scale production lines, where internal variables outperformed external variables (production, plate gaps and the dilution water flow rates) as inputs to ARMAX models for pulp and handsheet property estimations (Karlström and Hill 2014b,c). This statement can be seen as obvious since the process always capture incoming disturbances, which in the end affect the fiber pad and thereby the internal states in contrary to the external variables which cannot track the dynamics in such disturbances.

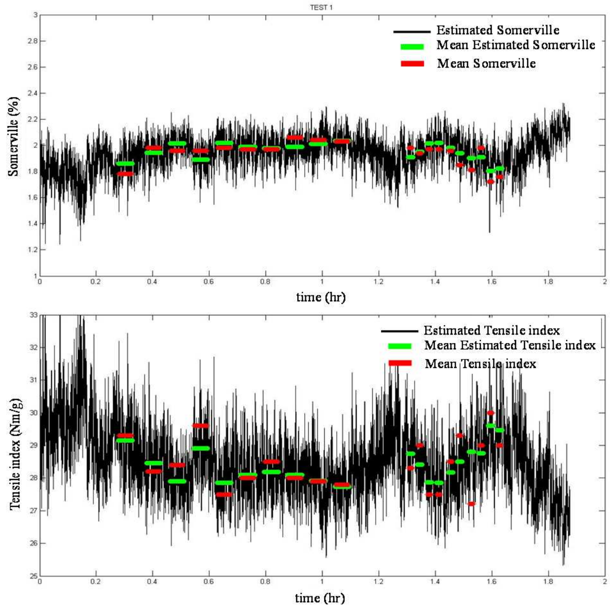


Fig. 11 - Estimated and measured tensile index and Somerville from a full-scale TMP production line (CD-82 refiner with temperature sensor arrays mounted in both the flat zone and the conical zone to estimate consistency and fiber residence time).

Later on it was shown that adding specific energy as an extra input to the ARMAX model does not improve the prediction. The reason refers to the fact the specific energy cannot capture the distributed phenomena caused by different segment pattern etc. along the refining zone radius. It was argued that the local phenomena are certainly important for the fiber development and ultimately the pulp and handsheet properties (Karlström et al. (2015a). Moreover, it was shown that further simplifications of the ARMAX model are possible using an ARX model structure (Ljung 1997) when studying pulp property variations Without a deeper description of details in this summary of results it was also shown that the dynamics in terms of the A polynomial poles (describing the primary time constant) were maintained unchanged while the gain in the model prediction can change significantly over time and different operating conditions. It was also shown that pre-specified pulp and handsheet properties can be reached by manipulating internal variables according to the low-frequency gains (Karlström et al. 2015b,c).

By using this concept an alternative to the traditional theories, which normally are focused on external variables as predictors, could be formulated. To illustrate this a schematic drawing is given in *Fig 12*. In this figure, the external variables are fed into the extended entropy model which provide the internal variables for further analysis.

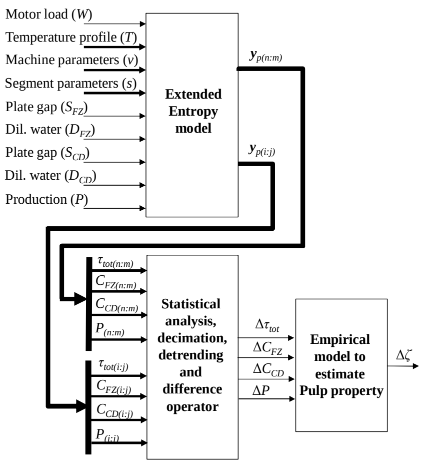


Fig 12 - Schematic description of the models used when analyzing pulp properties. Dense arrows represent vectors.

In the literature, the need to assure pulp and handsheet properties in a dynamic perspective are recognized. Among some of the wise statements were early formulated Forgacs (1963). He stated that

"Ideally, the measurements made on the pulp should be such that they can be interpreted in terms of the mechanical pulping operation, and at the same time be used to predict the paper or board making potential of the pulp."

Forgacs (1963) also reflected on the necessity to link the variations in the mechanical pulping process variables to the composition of particle shapes and sizes in the pulp. All this is by now well-known but still difficult to fully understand and communicate on a daily basis, even though the process computers are now linked to on-line pulp sampling devices, laboratory databases etc.

One reason why Forgacs' statement is even more important today is that mill-wide systems, in general, provide a huge amount of information that is sometimes impossible to handle from a follow up perspective due to problems understanding what actually happens inside the refining zones. This statement was followed up and tested for ChemicalThermoMechanicalPulp (CTMP) processes (Karlström and Hill (2016a). The main idea was to propose a methodology to estimate pulp and handsheet properties to start with and link these data to the daily process operation. Another idea was to verify earlier findings and compare external variables (dilution water feed rate, specific energy and plate gaps) with internal variables (consistency and fiber residence time) as predictors in multilinear models for three similar measurements; Scott-Bond, Z-strength and tensile index as dependent variables. The analysis was based on process data from a CD-82 refiner and comprised three different chip mixtures – 100% saw mill, 65% saw mill and 35% roundwood and finally 100% roundwood.

From a laboratory test program perspective, the test program was extensive and covered 80 test points where pulp samples were taken from the blow-line valve over a period of 3 minutes each similar to the procedure described above. Thereafter, the pulp samples were homogenized carefully and double tested. In total 2x51 samples of Scott-Bond, Z-strength and tensile index where used.

The main results was that the use of internal variables (residence time and consistency in the flat zone and CD-zone, respectively) as predictors also in this application outperform the external variables (plate gap and dilution water feed rate in the flat zone and CD-zone together with the specific energy) in the polynomial fit, and this was even more pronounced when validating the models using a holdout set. It was also shown that mixing internal and external variables as predictors will not yield better models. Applying a Principal Component Analysis (PCA) (Jolliffe (2002)) where the principal components with larger associated variances represent interesting dynamics, it was shown that the internal variables explain about 95% of the total variance using only three principal components while external variables required six principal components. Another important result was that the methodology can assure data quality and this made it possible to model Scott-Bond, Z-strength and tensile index independently of the type of chip mixture when internal variables were used (Karlström and Hill 2016a).

To overcome the tedious procedures to analyze laboratory data by visual inspection, a computer based algorithm was introduced to analyze any pulp and handsheet property available (Karlström and Hill 2016b). The following pulp and handsheet properties were analyzed more systematically:

CSF Freeness, sheet density, tensile strength, tensile index, elongation to rupture, tensile energy absorption, tensile energy absorption index, tensile stiffness, tensile stiffness index, tear strength, tear index, sheet crush test index, ISO brightness, Scott-Bond, Z-strength, shives(≥0.3mm), long fibers and fines.

The test series comprised in total 160 pulp samples, but only 19x102 pulp and handsheet properties were analyzed. Karlström and Hill (2016a) showed that an adjusted $R^2>0.85$ is required to pre-define as an acceptable level in the polynomial fit. It was also shown that the use of mean values of the handsheet properties deteriorates the final model prediction considerably.

Furthermore, it was argued that the input dynamics must be considered simultaneously as a minimum number of events per variable (EPV)>4 are assured according to the theory discussed by Harrell et al. (1985) and Freedman and Pee (1989). They demonstrated that the Type I error was inflated when the ratio of the number of variables to the number of observations was greater than 1/4, which corresponds to an EPV<4. Concato et al. (1995) and Peduzzi (1995, 1996) suggested increasing that number to at least 10 events per variable analyzed to maintain the validity of the final model. This analysis was based on data from a cardiac trial with good quality data and, in our situation, this recommendation would result in at least 50 samples if 5 predictors are used. Draper and Smith (1998) also suggested the use of an EPV of 10 as a good choice. In most cases this is not possible to apply in the pulp and paper industry due to tedious laboratory analysis. Vittinghoff and McCulloch (2007) conducted a large simulation study of other influences on confidence interval coverage, type I error, relative bias and other model performance measures and found a range of circumstances in which coverage and bias were within acceptable levels despite an EPV less than 10. They concluded that the "one in ten" rule can be relaxed. Karlström and Hill (2016a) showed that the original proposal of Freedman and Pee (1989) can be followed as an initial setting and that reliable models can be derived using an EPV≈4. However, to reach an adjusted $R^2>0.85$ in all pulp and handsheet properties at the same time as the major dynamics in the process are captured requires a lot of data. As an examples Karlström and Hill (2016b) showed that out of the 19x102 pulp and handsheet properties only about 19x50 where accepted, i.e. in this case the "one to ten" rule was possible to follow. This gives a hint about how many samples we need to reach an assured data base for future use. To illustrate the findings in more details the reader is referred to the methodology outlined by Karlström and Hill (2016a,b). In short the following was found;

It is obvious that the tensile index, Scott-Bond and Z-strength are related to each other which also was shown by Karlström and Hill (2016a). It is also interesting to compare CSF Freeness with shives (≥0.3 mm), long fibers and fines. The correlation between CSF Freeness and tensile index, Scott-Bond and Z-strength are poor while it was a strong correlation between sheet density, tensile index, Scott-Bond and Z-strength as expected see *Table 1*.

To give a glimpse about the modeling accuracy, *Table 2* is attached to summarize the findings. Note, Case I includes residence time and consistency in the flat zone and the CD-zone as predictors. Case II includes the specific energy as well as an added input to the model, see *Table 3*.

Table 1: Matrix of the correlation coefficients between each pulp and handsheet property obtained using the models derived in Karlström and Hill (2016b).

Correlation coefficients for all properties																			
No.	**PROPERTY**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1	CSF Freeness	1	-0,70	-0,16	-0,24	-0,09	-0,47	-0,31	-0,24	0,45	0,14	0,10	-0,40	0,59	-0,50	-0,34	-0,75	0,67	0,37
2	Sheet density		1	0,53	0,86	0,77	0,94	0,61	0,38	0,24	-0,13	-0,11	0,86	0,16	0,93	0,87	0,24	0,06	0,02
3	Tensile strength			1	0,66	0,69	0,41	0,04	0,73	0,34	-0,83	-0,83	0,22	0,34	0,40	0,49	-0,15	0,24	0,55
4	Tensile index				1	0,99	0,93	0,56	0,36	0,62	-0,14	-0,14	0,86	0,63	0,88	0,94	-0,19	0,55	0,30
5	Elongation to rupture					1	0,86	0,49	0,36	0,70	-0,17	-0,18	0,80	0,74	0,81	0,90	-0,31	0,66	0,38
6	Tensile energy absorption						1	0,62	0,15	0,40	0,10	0,12	0,97	0,42	0,93	0,97	0,09	0,33	-0,03
7	Tensile energy absorption index							1	0,39	0,60	0,36	0,27	0,71	0,25	0,84	0,43	-0,31	0,26	0,35
8	Tensile stiffness								1	0,37	-0,68	-0,76	0,04	0,04	0,38	0,07	-0,31	0,01	0,79
9	Tensile stiffness index									1	0,10	0,01	0,45	0,87	0,51	0,40	-0,88	0,89	0,75
10	Tear strength										1	0,99	0,31	0,10	0,09	0,01	-0,05	0,17	-0,43
11	Tear index											1	0,32	0,07	0,07	0,06	0,05	0,13	-0,54
12	Sheet crush test index												1	0,44	0,93	0,92	0,02	0,38	-0,06
13	ISO brightness													1	0,35	0,53	-0,74	0,99	0,48
14	Scott-Bond														1	0,83	-0,06	0,29	0,20
15	Z-strength															1	0,07	0,43	-0,04
16	Shives(>=0.3mm)																1	-0,81	-0,82
17	Long fibers																	1	0,51
18	Fines																		1
Represents abs(0.7)=<Corr=<abs(0.9)		Note I: the correlation coefficients are estimated based on the total data set of estimated property																	
Represents Corr>=abs(0.9)		Note II: The correlations are derived using Case I (predictors;res. time and consistency) as a rule model.																	

Table 2: <u>Modeling</u> of pulp and handsheet properties based on a selected data set of ranked measurements in the 5th step. The adjusted R^2 is used as a measure of the goodness of fit for each property exceeding 0.85.

Modeling of ranked properties					
Property	**Total # of ranked samples**	**# of samples for modeling**	**Case I Adj. R2**	**# of samples for modeling**	**Case II Adj. R2**
CSF Freeness	92	45	0,858	46	0,853
Sheet density	61	61	0,857	61	0,857
Tensile strength	65	53	0,857	53	0,861
Tensile index	71	52	0,851	51	0,865
Elongation to rupture	88	50	0,859	50	0,856
Tensile energy absorption	72	52	0,850	52	0,854
Tensile energy absorption index	94	45	0,862	45	0,859
Tensile stiffness	72	53	0,857	54	0,857
Tensile stiffness index	84	56	0,851	55	0,857
Tear strength	66	66	0,871	66	0,871
Tear index	58	58	0,933	58	0,932
Sheet crush test index	48	48	0,956	48	0,969
ISO brightness	78	64	0,856	65	0,860
Scott-Bond	59	59	0,877	59	0,883
Z-strength	43	43	0,917	43	0,917
Shives(>=0.3mm)	66	66	0,877	66	0,877
Long fibers	81	59	0,861	59	0,861
Fines	60	53	0,852	52	0,858

Table 3: Parameters for Case I for all pulp and handsheet properties studied. Note, when using the parameters the consistency must be given in %, fiber residence time in seconds and specific energy in kWh/ADMT.

Model parameters - Case I						
Properties	**Intercept**	**Cons.(FZ)**	**Cons.(CD)**	**R.time(FZ)**	**R.time(CD)**	**Spec.E**
CSF Freeness	767,4522	6,5706	-5,3285	-320,0951	1430,6061	
Sheet density	311,3555	-13,5518	7,6204	100,8509	55,8056	
Tensile strength	-3,5278	-0,1770	0,0831	-3,6486	62,7926	
Tensile index	40,2999	-2,1925	1,0245	-16,5077	200,9831	
Elongation to rupture	1,6649	-0,0341	0,0143	-0,7405	6,0259	
Tensile energy absorption	80,0754	-4,2263	2,2176	-38,5411	314,1703	
Tensile energy absorption index	0,4283	-0,0111	0,0046	0,7856	-4,6984	
Tensile stiffness	-451,7375	-5,3301	1,3169	1757,0678	-6261,3361	
Tensile stiffness index	5,2630	-0,0675	-0,0026	0,5462	-1,9310	
Tear strength	6435,5391	-14,0063	0,2833	811,0374	-25020,3831	
Tear index	53,1587	-0,1836	0,0703	-5,6864	-140,9302	
Sheet crush test index	24,1904	-0,6072	0,3068	-1,8931	10,6965	
ISO brightness	88,6031	-0,7198	0,0572	-57,3180	331,3528	
Scott-Bond	155,0146	-7,2287	3,5924	120,7834	-508,4503	
Z-strength	144,0442	-6,0570	3,1333	-129,1267	890,5317	
Shives(>=0.3mm)	-1787,1167	-53,8174	94,7427	-1459,5470	10070,7017	
Long fibers	8,0583	-0,0944	-0,0102	-8,7292	47,3025	
Fines	34,3848	0,2466	-0,6137	70,0445	-240,6360	

To illustrate what the modeling efforts will bring to future applications we study how Scott-Bond, sheet density and shives (≥0.3mm) are changing dynamically if the models are expanded into the time domain, see *Fig. 13* for the entire period. Moreover, to fully understand the statements given above the normalized values of predictors are given for a short period to get a reasonable resolution in *Fig. 14.*

When studying *Fig. 14* together with the normalized estimated variables Scott-Bond, sheet density, shives and Z-strength and tensile index in *Fig. 15*, it is shown that when the relation between Scott-Bond and sheet density is optimized it is favorable to reduce the dilution water to the CD-zone at the same time as a small plate gap is preferred. This is not praxis in normal process operation and should be studied further.

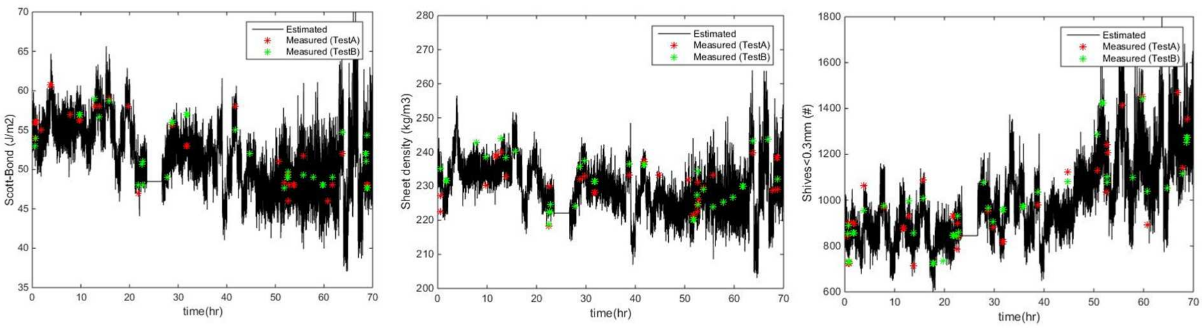


Fig. 13: Estimated and measured (TestA and TestB) Scott-Bond, sheet density and shives (≥0.3mm).

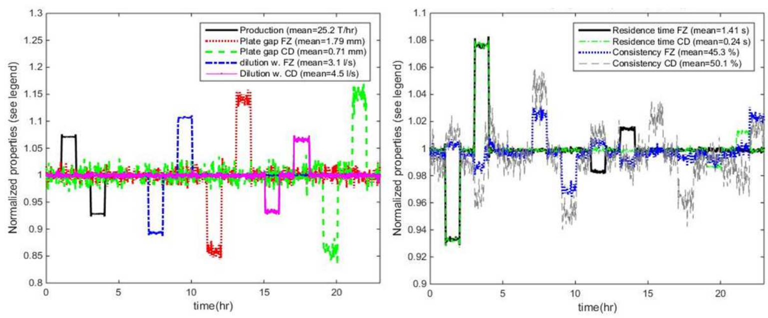


Fig. 14: Normalized properties: Upper figure: Production, plate gap and dilution water. Lower figure: Residence time and Consistency.

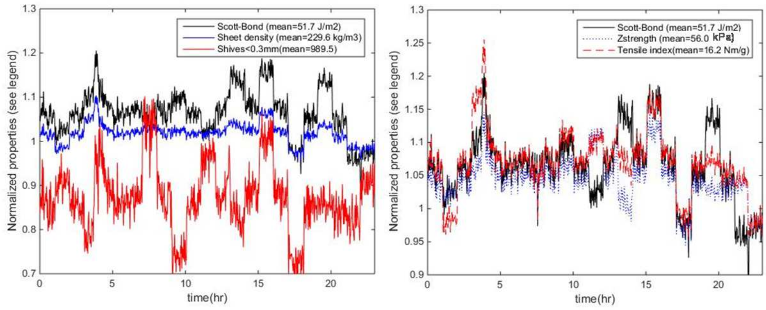


Fig. 15: Normalized properties: Upper figure: Estimated Scott-Bond, sheet density and shives (≥0.3mm). Lower figure: Estimated Scott-Bond, Z-strength and tensile index.

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