Aalto University
School of Chemical
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School of Chemical Technology
Degree Programme of Bioproduct Technology

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IMPROVING THE EFFICIENCY OF A BROWN STOCK WASHING LINE

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 23 September, 2014.

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Abstract of master's thesis

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Abstract

The objective of this Master's thesis was to improve the efficiency of a brown stock washing line. To improve the efficiency upper level control system and real-time measuring devices were utilized.

The experimental part of this thesis deals with the introduction and development of an upper level control system and refractometers, as well as the trials carried out to measure the performance of the new installations. Furthermore, trials were carried out to find the optimum values for operation parameters so that the washing line could be operated in an economically and environmentally sustainable manner. The parameters included were dilution factor, drum torque, feed consistency and production rate.

The results suggest that by using an upper level control system to control the dilution factor of the entire brown stock washing line, by real time wash loss measurements as feedback and by torque control of the washers it is possible to reduce the amount of brown stock wash loss and simultaneously decrease the amount of used wash water. The obtained decrease in wash loss and wash water usage significantly lowers the costs resulting in bleaching plant and evaporation plant, as well as environmental burden.

Keywords Brown stock washing, upper level control, wash loss, refractometer

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Tiivistelmä

Tämän työn tavoitteena oli parantaa sellun ruskean massan pesulinjan tehokkuutta. Tehokkuuden parantamisen työkaluina käytettiin ylemmän tason säätöä ja reaaliaikaisia mittalaitteita

Kokeellinen osa keskittyy ylätason säädön ja refraktometrien käyttöönottoon ja kehittämiseen, sekä suoritettujen koeajojen tuloksiin. Koeajojen tavoitteena oli mitata uusien laitteiden ja säätöpiirien toimivuutta ja suorituskykyä. Lisäksi koeajojen avulla pyrittiin löytämään optimaaliset ajoparametrit niin, että pesulinjaa pystyttäisiin ajamaan kustanustehokkuuden ja ympäristöpäästöjen kannalta kestävällä tavalla. Koeajoissa muutettavina ajoparametreinä käytettiin laimennustekijää, pesurummun momenttia, syöttöpainetta ja tuotantonopeutta.

Tulokset osoittavat, että käyttämällä ylemmän tason säätöä koko ruskean massan pesulinjan laimennustekijän hallintaan, käyttämällä reaaliaikaisia pesuhäviömittäreita pesuhäviömääritykseen ja momenttisäätöä pesurummun nopeuden säätämiseen, voidaan ruskean massan pesuhäviötä pienentää ja samanaikaisesti pienentää pesulinjalla käytetyn pesuveden määrää. Saavutettu vähennys pesuhäviössä ja pesuveden käytössä pienentää merkittävästi valkaisuvaiheen ja haihduttamon kustannuksia ja pienentää ympäristökuormaa.

Avainsanat Ruskean massan pesu, ylätason säätö, pesuhäviö, refraktometri

Preface

This thesis was made in co-operation with UPM-Kymmene, Aalto University, K-Patents and Metso Automation. The experimental part was carried out at the UPM-Kymmene Kaukas Pulp mill in Lappeenranta between September 2013 and April 2014.

During the thesis I became more aware of the challenges and possibilities related to brown stock washing and I experienced and understood the complexity of the process. I learned a lot and I can only pay tribute to the experts working in the field; it takes commitment and hard work, and requires creativity.

I express my deep gratitude to the instructor of the thesis M. Sc. Marko Sundqvist for guidance, support, and inspiring collaboration. I want to thank my second instructor M. Sc. Riku Kopra for valuable technical advices and guidance in the academic part of the thesis. I am grateful to Professor Olli Dahl who offered his wide experience in the field, providing practical ideas and academic advices. Moreover, my warm thanks go to Esko Kamrat for his help and support with the measurement technology.

My thanks are extended to the personnel of the brown stock washing line for sharing their expertise and helping in the development of the control system. Furthermore, I owe my gratitude to the personnel in the pulp laboratory for their constant and vitally important help with the analyses.

I hope research will continue active in the field of brown stock washing. There are many possibilities to tame this savage process.

ABBREVIATIONS AND SYMBOLS

ADt	Air dry metric ton
AOX	Adsorbable organic halogens
APE	Actual Process E-value
BDt	Bone dry metric ton
COD	Chemical oxygen demand
DF	Dilution factor
DR	Displacement ratio
DS	Dissolved solids
ROI	Return on investment
TDS	Total dissolved solids
UV	Ultra Violet
E	Efficiency value
Evap	Evaporation
L	liquor flow
L_0	Unwashed pulp stream
L_1	Washed pulp stream
nD	Refractive index
R	Wash liquor ratio R
S	Shower flow
V_1	Filtrate stream
V_2	Wash liquor stream
W	Wash liquor ratio W
X_0	Concentration in feed pulp
X_1	Concentration in discharge pulp
Y	Wash yield
Y_1	Concentration of wash filtrate
Y_2	Concentration of wash liquor
ϕ	Consistency
λ	Wave length

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1. Introduction

Good performance of the brown stock washing line is important for the whole pulp mill considering the mill's energy consumption and environmental load, as well as the pulp quality. In the control of the line various, sometimes contradictory objectives have to be achieved. These objectives include cleanliness of pulp, chemical and organic matter recovery, minimum evaporation need for black liquor and minimum environmental load. The most favourable economic and environmental result is obtained when the pulp is washed as clean as possible with as little washing water as possible.

To achieve an effective trade-off between the before mentioned objectives of brown stock washing, comprehensive and precise control of the washing line is needed. An effective control requires both proper inline monitoring of the wash loss and an upper level control system to adjust the water usage and other key parameters of the whole washing line.

The literature review discusses theory of pulp washing, starting from the mechanisms and moving on to the evaluation of performance and result, where different methods to evaluate wash loss are presented and compared. The third chapter discusses the control of an individual DD-washer and the advanced control of an entire washing line. The literature review concludes in an economic analysis of brown stock washing, where cost effectiveness and economic implications of brown stock washing for the whole pulp mill are discussed. In addition, the decision to invest on an advanced control system is discussed.

In the experimental part the performance obtained by the installed control system and inline refractometers was tested. The performance was analysed as dissolved solids to evaporation and wash loss to bleaching. Effect of operational parameters such as dilution factor, drum torque and feed consistency on wash loss was tested. Furthermore, conductivity and dissolved solids were compared as inline wash loss measurements.

2. Brown stock washing

2.1 Theory

Purpose of brown stock washing

The primary purpose of brown stock washing is to remove the impurities from the pulp and recover the soluble organic matter for energy production and the cooking chemicals for regeneration. The removal of soluble substances should be done with as little water as possible and at the same time the pulp should be as clean as possible. These objectives are somewhat contradictory and the challenge is to create a compromise which delivers an economic and environmental optimum.

Pulp cleanliness in its introduction to bleaching stage is important from both economic and environmental aspects. It strongly influences the amount of bleaching chemicals needed in bleaching stage, as the chemicals are used to oxidize and extract the unwanted material left in the pulp. The cleaner the pulp is after washing, the fewer chemicals have to be used. From the environmental point of view high bleaching chemical consumption is not desirable, since it leads to an increased load to the environment. Furthermore, dirty pulp in bleaching might result in the formation of environmentally hazardous compounds. From the economic point of view, the use of bleaching chemicals is expensive. Moreover, pulp cleanliness might enhance the quality of the fibres.

Sufficient wash water has to be used in order to achieve adequate pulp cleanliness. Nevertheless, excess water used in washing stage brings economic burden since water has to be separated from black liquor by costly evaporation. In addition to the economic concern, evaporation consumes large quantities of energy which in turn might lead to environmental stress. (1)

Washing mechanisms

The washing process is based on two operations: dilution/extraction and displacement washing. All pulp washing is based on these two principles.

In dilution/extraction washing, the pulp slurry is first diluted with weaker washing liquor, then mixed and thickened by filtering or pressing. Dilution/extraction is done as many times necessary to achieve the required washing result. In theory, to achieve the same stock slurry concentration as in the washing liquid, an unlimited number of dilution/extraction phases are needed. The effectiveness of this mechanism is considered rather poor and it is dependent on the consistencies to which the pulp is diluted and thickened. (1) (2) (3)

In displacement washing, the black liquor in the pulp mat is displaced with weaker washing liquor or water. Mixing at the interface of the washing liquid and black liquor is essential in this method. The lesser the mixing occurs; the better is the washing result. Figure 1 depicts the principle of ideal displacement washing. In theory, if no mixing would occur the displacement would take place with 100 percent effectiveness. However, mixing at the interface always takes place to some degree. Due to the mixing at the interface, more washing liquid and/or more washing stages have to be used to obtain the desired washing result. Moreover, in order to be displaced, the solute sorbed onto the fibres would demand more time to diffuse out of the fibres. (1) (2) (3)

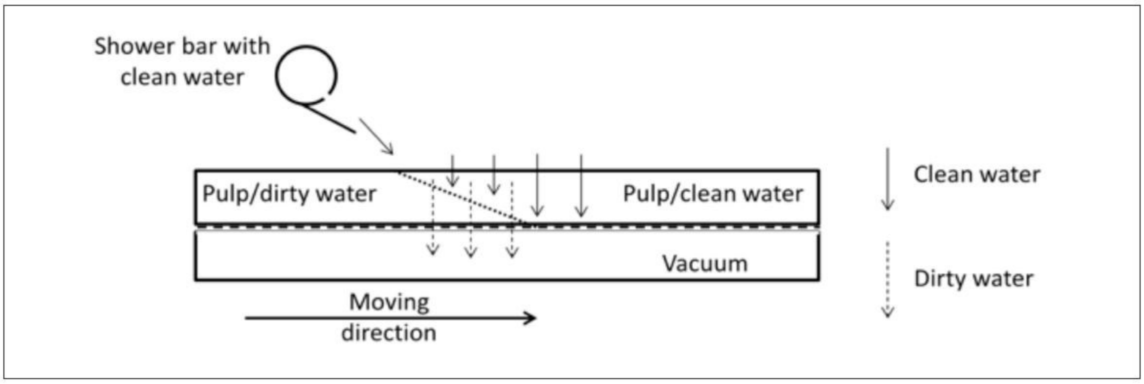


Figure 1. Principle of displacement washing. (4)

Multistage and fractional washing

Modern brown stock washing lines are multistage lines. They comprise of several washers, each of which may consist of various washing stages. Normally pulp washers are set so, that the washing liquid runs counter current to the pulp stock. The clean washing liquid is fed to the last washer of washing line, where the pulp is cleanest. This arrangement, depicted in Figure 2, enables washing of cleanest pulp with cleanest liquid and dirtiest pulp with dirtiest liquid. The idea of the counter current washing is to utilize the same washing liquor for washing in all washers, thus substantially improving the mills water economy and environmental footprint (3)

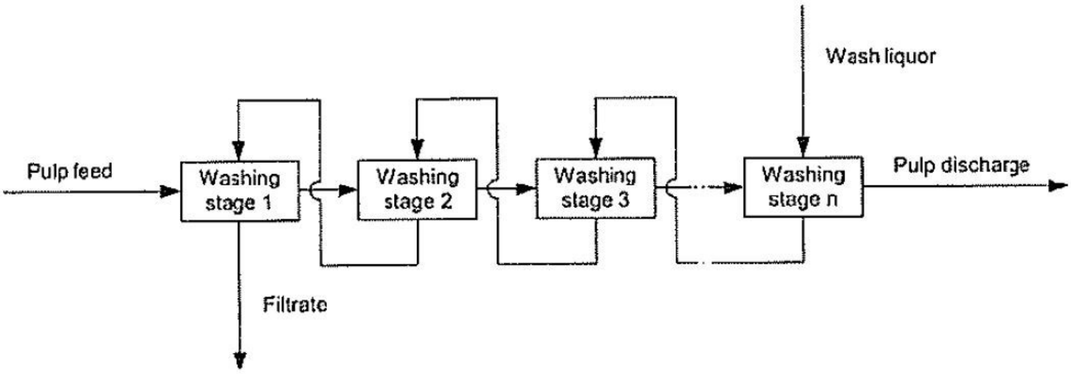


Figure 2. Pulp washing using counter current principle. (3)

The same counter current principle is applied in individual multistage washers, where the washer is divided into sections and the washing liquid contains different concentrations in every section. The principle is to obtain more washing stages with the same wash water consumption, thus improving the washing efficiency. Figure 3 illustrates the principle of a two stage fractional washing, where the washing liquid is divided in two parts; cleaner and dirtier. The cleaner filtrate of the second washing stage (2/2) is directed to the cleaner part of the first stage (1/2). In the same manner the dirtier filtrate of the second stage (2/1) is directed to the dirtier part of the first stage (1/1). (1) (3) (5)

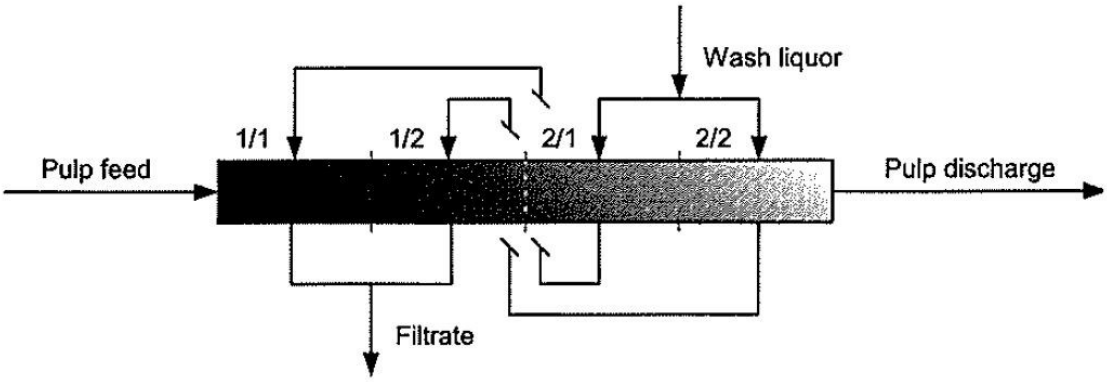


Figure 3. Principle of a two stage fractional washing (3)

Diffusion

In pulp washing there is a certain portion of liquid that is not washable by physical operation. This is the bound liquid inside fibre voids. The only way dissolved substances can transfer from inside the fibre to the free liquid outside the fibre is trough diffusion. Diffusion happens due to a difference in concentration between the liquid in the fibre void and the free liquid. Diffusion rate is relative to the concentration difference so that it is faster with larger concentration differences. (6) (7)

Diffusion rate depends on molecular structure. In brown stock washing diffusion takes place in fast and slow phase. The small sodium ions diffuse fast equilibrating the concentration difference in seconds, while large molecules such as lignin take hours or even days to diffuse. There are a number of factors affecting diffusion. Diffusion time shortening factors include large concentration difference, long washing time and storage time, high temperature and small ion concentration. Kovasin (8) suggests that diffusion has a significant effect only in Hi-Heat washing. Solely in Hi-Heat washing temperature and delay are high enough to result in significant diffusion. Figure 4 depicts an experiment on how diffusion coefficient follows the theoretical Stokes-Einstein equation until 70 °C and then starts to grow rapidly. It can be seen that between 80 °C and 90 °C the diffusion coefficient increases by fivefold. (6)

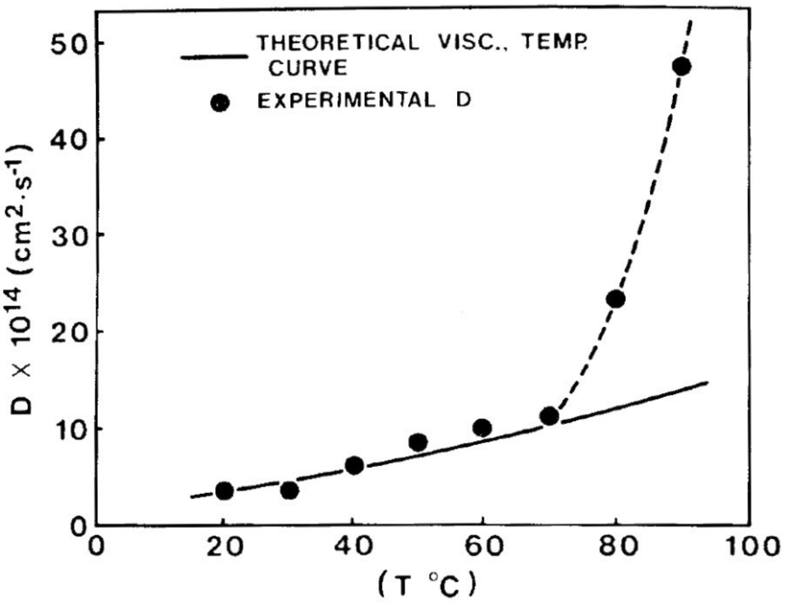


Figure 4. The effect of temperature on intrafiber diffusion coefficient. (9)

2.2 Evaluating performance

Brown stock washing performance and washing result have been studied for decades. At least since the 1950s several mathematical methods have been developed to define the performance of washing. Many mathematical evaluation methods have been created, followed by a number of modifications and adjustments.

Washer performance parameters

When studying washer performance, the washing process is often demonstrated using a black box model illustrated in figure 5. The model, originally developed by Nordén, consists of four streams: the inlet and outlet pulp streams, the wash liquor stream and the filtrate stream. Concentrations of dissolved solids in all four streams are also defined. L0 and L1 are pulp streams, expressed as tons of liquor/BDt. V1 and V2 are liquor streams, expressed as tons of liquor/BDt. X and Y are concentrations, expressed as kg of dissolved solids/BDt. (1)

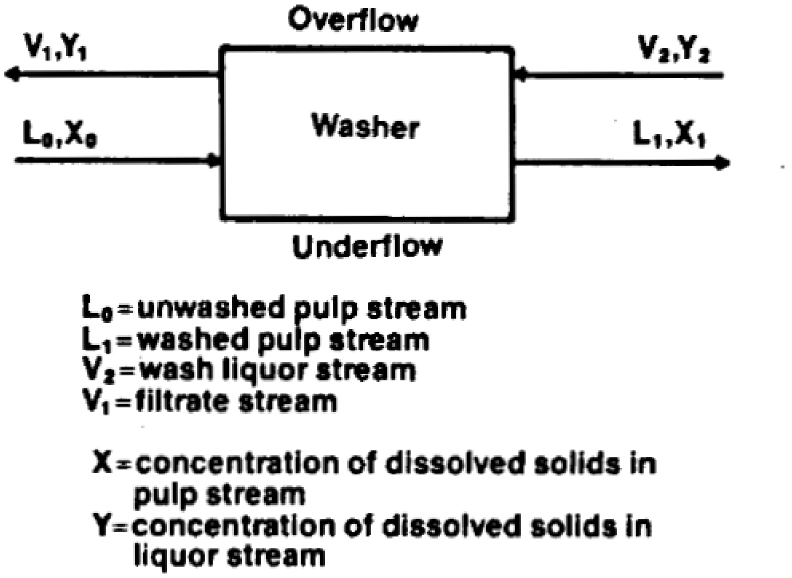


Figure 5 Generalized washing model (1)

Many mathematical indicators have been developed to define the performance of a washer or a washing line. The most commonly used parameters are presented in Table 1. Crotogino (1) divides these parameters into three following categories:

1. The amount of wash liquor used
2. The amount of solute removed
3. The efficiency of a pulp washer operating under standardized inlet and discharge consistencies

Table 1. Parameters to study washer performance

Name of parameter	Formula
Parameters for wash liquor usage	
Dilution factor, DF	$DF=V_2-L_1$ (1)
Wash liquor ratio, R	$R=V_2/L_1$ (2)
Wash liquor ratio, W	$W=V_1/L_0$ (3)
Parameters for solute removal	
Displacement ratio, DR	$DR=\frac{X_0-X_1}{X_0-Y_2}$ (4)
Wash yield, Y	$Y=1-\frac{L_1X_1}{L_0X_0}=\frac{V_1Y_1}{L_0X_0}$ (5)

The amount of wash liquor used to pulp produced is important in terms of evaporation load and sufficient wash water to achieve required washing loss. Dilution factor (DF) illustrated in equation 1 is the only wash water parameter calculated in relation to the pulp produced. Moreover, DF demonstrates the real load going to evaporation. For displacement washing, DF = 0 means that equal amount of wash water was used to displace the black liquor from the pulp.

The wash liquor ratios R, represented in equation 2 and W, in equation 3 are defined as liquor balances and remain approximately equal if there is no change in pulp inlet or outlet consistencies. These two parameters do not take into consideration the pulp stream, thus making dilution factor the most commonly used parameter to describe wash liquor usage.

Displacement ratio defined in equation 4 is a parameter determining the ratio of dissolved solids removed in washing. In an ideal case displacement ratio would be 1, meaning the displacement of all dissolved solid in pulp. DR is not the most suitable parameter to use when measuring washer efficiency, since the amount of wash liquor is not considered. Even inefficient washer can achieve high DR, if large quantity of washing liquid is used. Nevertheless, it can be used to measure effectiveness, if DF is known. (8)

E-value described in equation 6 indicates washing stage efficiency, taking into account the used washing liquid. Nordén has defined the parameter as “the number of ideal mixing stages in series with a complete mixing of underflow and overflow that is required to achieve the same departing overflow and underflow as those of the washing stage”. E-value is applicable to any washing operation, since it makes no reference to the internal functioning of the washing, only to the internal functioning of the model. (10) (11)

$$E = \frac{\ln \frac{L_0}{L_1}\left(\frac{X_0 - Y_1}{X_1 - Y_2}\right)}{\ln\left(V_2 / L_1\right)} \qquad (6)$$

Determining the inlet consistency of a washer has been noted to be difficult in mill circumstances. As a solution for this a modification of the E-value, E_{APE} was created. E_{APE} defined in equation 7 does not use inlet stock information, thus making it a more suitable parameter for operation in mill site. APE is an abbreviation of Actual Process E-value.

$$E_{APE} = \frac{\ln\left(1 + \frac{DF(Y_1 - Y_1)}{L_1(X_1 - Y_2)}\right)}{\ln\left(1 + V_2 / L_1\right)} \qquad (7)$$

E-value for the entire washing line can be calculated summing individual E-values, as demonstrated in equation 8.

$$E \ln R = E_1 \ln R_1 + E_2 \ln R_2 + \ldots + E_n \ln R_n \qquad (8)$$

Many measurements and analysis are needed to gather the data required for performance evaluation. This is challenging especially due to the dynamic behaviour of the brown stock washing line. There is often not enough data to give sufficient and reliable information on sudden changes in the process. On-line washing loss measurements have been used increasingly in order to get real time information on process conditions and to adjust the process respectively. Methods to measure process conditions are presented more closely in the following chapter. Although measurement devices have developed to be more versatile and accurate, process lag times and instability continue to offer challenges in performance monitoring.

2.3 Evaluating result

Wash loss

In brown stock washing, wash loss indicates the amount of dissolved organic and inorganic matter, which could not be removed during the washing stage. Many parameters have been used to evaluate wash loss. The used parameters have changed during the years, depending on the interest of the industry. Sodium loss was widely used when recovery of cooking chemicals was the most important parameter in washing. Sodium loss is a typical indicator to describe the wash loss in washing. It is a good parameter to describe the cooking chemicals lost, but this method does not take into consideration organic and other inorganic compounds in pulp suspension. (12) (13)

When environmental concerns started to rise and O_2-stages became more common, it became increasingly more important to characterize the wash loss in terms of organic solids. Consequently, chemical oxygen demand (COD) has partly replaced sodium loss as a washing loss indicator. It is used to express the organic matter lost in washing, as well as an indicator of bleaching chemical load needed in bleaching. Subsequently, the COD can be used to assess the organic load to the environment. (12) (13)

Today inline real time measurements are gaining more popularity in wash loss evaluation. The measured parameters are mostly Total Dissolved Solids (TDS), conductivity and dissolved lignin. TDS measures all dissolved material in the solution, making emphasis on lignin content. Conductivity makes more reference to inorganic material in a solution, whereas dissolved lignin measurement measures only lignin. (12) (13)

Sodium

In the early years of brown stock washing the recovery of cooking chemicals was seen as the most important factor of washing due to the rather expensive chemicals. The amount of sodium in pulp suspension has traditionally been used as an indicator of washing loss, generally expressed as kg Na_2SO_4/BDt. Sodium loss illustrates the amount of sodium escaping from the chemical recovery cycle. Nevertheless the disadvantage of this method is the fact that it does not consider lignin and other organic substances. Moreover, the amount of organic substances cannot be identified with sufficient accuracy, by determining sodium and using a correlation curve, due to the ever-changing conditions of a washing line. Is to say, even small changes in conditions change the correlation between sodium and organic matter. Figure 6 illustrates how the correlation between COD washing loss and sodium loss can vary between different mills. (14) (12)

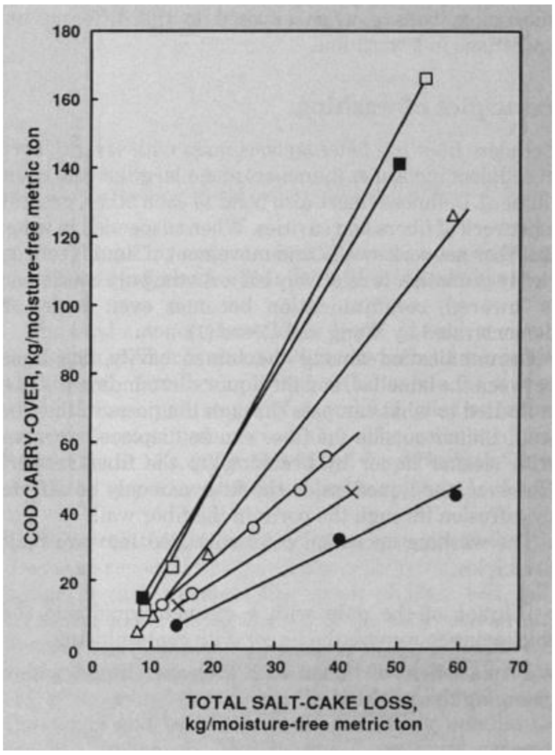


Figure 6. Correlation between COD- and sodium based washing loss. (14)

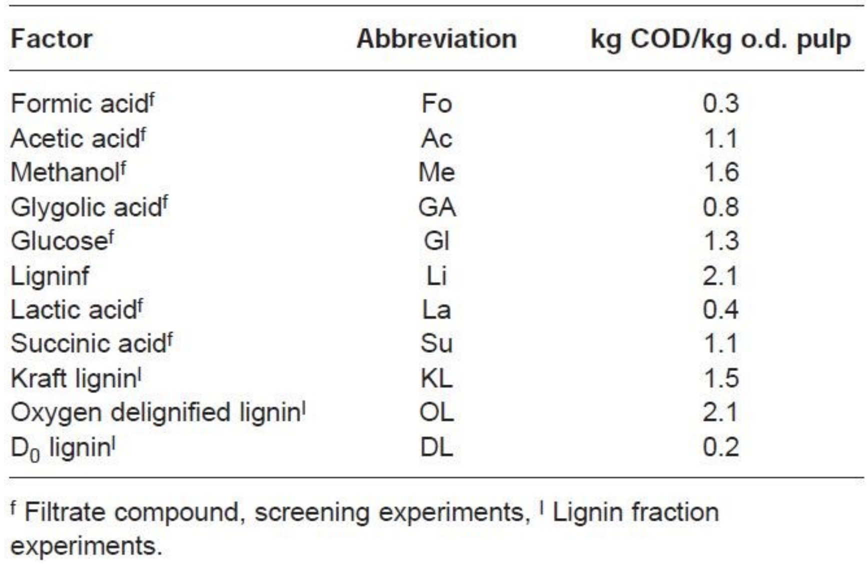
Sodium and other inorganic substances in washing line are ionic and represent a rather good correlation with conductivity. Thus, conductivity is widely used to measure sodium loss. Furthermore, conductivity measurement is widely made inline and used to monitor and operate the washing line. Conductivity is affected by pH, which should be considered in the measurement, more so if there are large changes in operation conditions or changes in wood species. Moreover, conductivity is affected by temperature. (13)

Chemical oxygen demand (COD)

As the industry has started to take the environment more into consideration, it has become important to define the organic washing loss from brown stock washing. An important disadvantage of organic washing loss is the fact that the organic substances can be converted to chlorinated organic compounds in first conventional stage of bleaching and be discharged as harmful AOX (adsorbable organic halogens). Moreover, organic washing loss increases bleaching chemical consumption and therefore bleaching cost. To determine the organic wash loss, chemical oxygen demand is widely used in the industry. COD is expressed as the amount of oxygen equivalent consumed by a one liter of sample, using a specific procedure (13). It can be expressed as filtrate COD (mg / ml), or as total COD, (COD/BDt) which is the COD in both fiber voids and filtrate. (12) (13)

In his study, Botta (15) finds COD as a good indicator, because it depicts the amount of organic substances, which is increasingly important. As COD levels from pulp mills effluents are strictly regulated due to environmental reasons, COD loss is a useful parameter to monitor in washing. However, Viirimaa/Sankari (16) (17) (18) suggests that many compounds can generate significant COD as presented in table 2, but only few of them affect bleaching performance or oxygen delignification response. In continuation, only these few compounds can be called “real washing loss compounds”, due to the negative effect on bleaching performance. Table 3 represents the effect of the compounds on D0 stage responses.

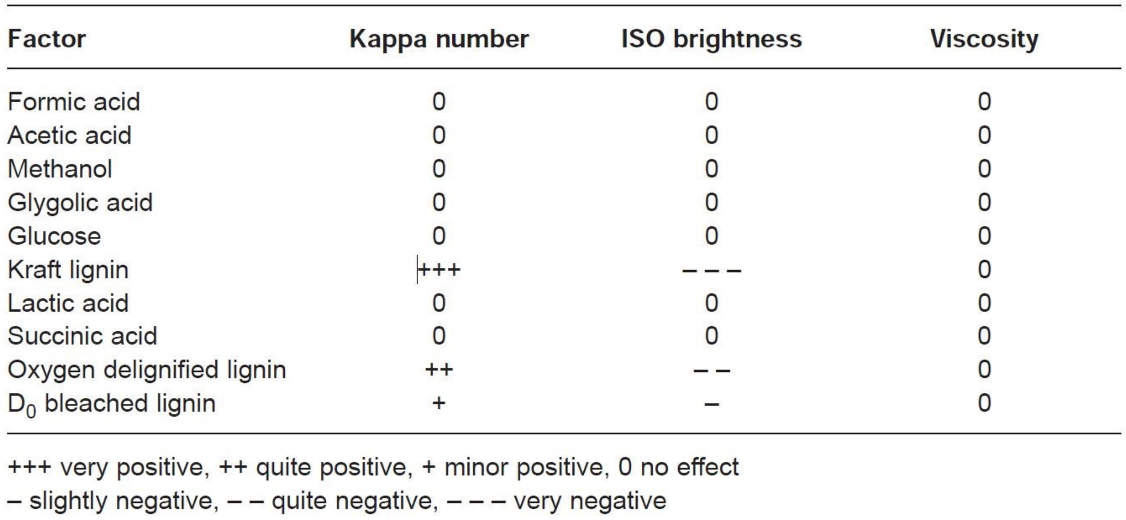
Table 2. Experimental COD levels of wash loss compounds. (16)



Factor	Abbreviation	kg COD/kg o.d. pulp
Formic acid^{f}	Fo	0.3
Acetic acid^{f}	Ac	1.1
Methanol^{f}	Me	1.6
Glygolic acid^{f}	GA	0.8
Glucose^{f}	Gl	1.3
Ligninf	Li	2.1
Lactic acid^{f}	La	0.4
Succinic acid^{f}	Su	1.1
Kraft lignin^{l}	KL	1.5
Oxygen delignified lignin^{l}	OL	2.1
D_0 lignin^{l}	DL	0.2

^{f} Filtrate compound, screening experiments, ^{l} Lignin fraction experiments.

Table 3. Effect of different washing loss compounds on responses in the D0 stage. (16)



Factor	Kappa number	ISO brightness	Viscosity
Formic acid	0	0	0
Acetic acid	0	0	0
Methanol	0	0	0
Glygolic acid	0	0	0
Glucose	0	0	0
Kraft lignin	+++	– – –	0
Lactic acid	0	0	0
Succinic acid	0	0	0
Oxygen delignified lignin	++	– –	0
D_0 bleached lignin	+	–	0

+++ very positive, ++ quite positive, + minor positive, 0 no effect
– slightly negative, – – quite negative, – – – very negative

Furthermore, Sillanpää (12) (19) stated COD as not a good tool to measure washing loss, and suggest the measurement of lignin instead. Other disadvantages of COD measurement are its weak repeatability and the rather long time delay from quite long analysis.

Total dissolved solids

Washing loss evaluation based on total dissolved solids (TDS) is simple, inexpensive and repeatable, when carried out in laboratory. For long it has been used for troubleshooting and experimental studies. The analysis is made simply by evaporating a liquor sample to constant dryness and indicating the result as % of dissolved solids. The laboratory determination is applicable for liquors only. (13)

During recent years, there have been many cases of using a continuous refractometer to measure TDS wash loss inline. Measurement is based on the determination of the refractive index (nD) of a process solution. Refractive index measurement is actually a measurement of the speed of light in a medium. The index is defined as the ratio of speed of light in vacuum divided by that in the medium. As the speed of light is highest in vacuum, refractive index is always higher than 1.

The inline refractometer determines the refractive index of the process solution by measuring the critical angle of refraction, using a yellow led light source with a constant wavelength. The relation between the refractive index and the concentration depends on the solvent and solute, temperature, and wavelength. By using a monochromatic light source to avoid the wavelength dependency and a thermometer to compensate the effect of temperature, the effect of dissolved solids on the refractive index is defined accurately, subsequently determining the concentration of dissolved solids. (20)

The principle of the refractive index measurement is illustrated in figure 7, where (L) is the light from the light source, directed to the interface between the prism (P) and the process solution (S). Two of the prism surfaces (M) bend the light rays so that they meet the interface at different angles. The reflected rays of light form an image (ACB), where (C) is the spot of the critical angle ray. The rays at (A) are totally internally reflected at the process interface, the rays at (B) are partially reflected and partially refracted into the process solution. So the optical image is divided into a light area (A) and a dark area (B). The position of the shadow edge

(C) indicates the value of the critical angle. The refractive index nD can then be determined from this spot. (20)

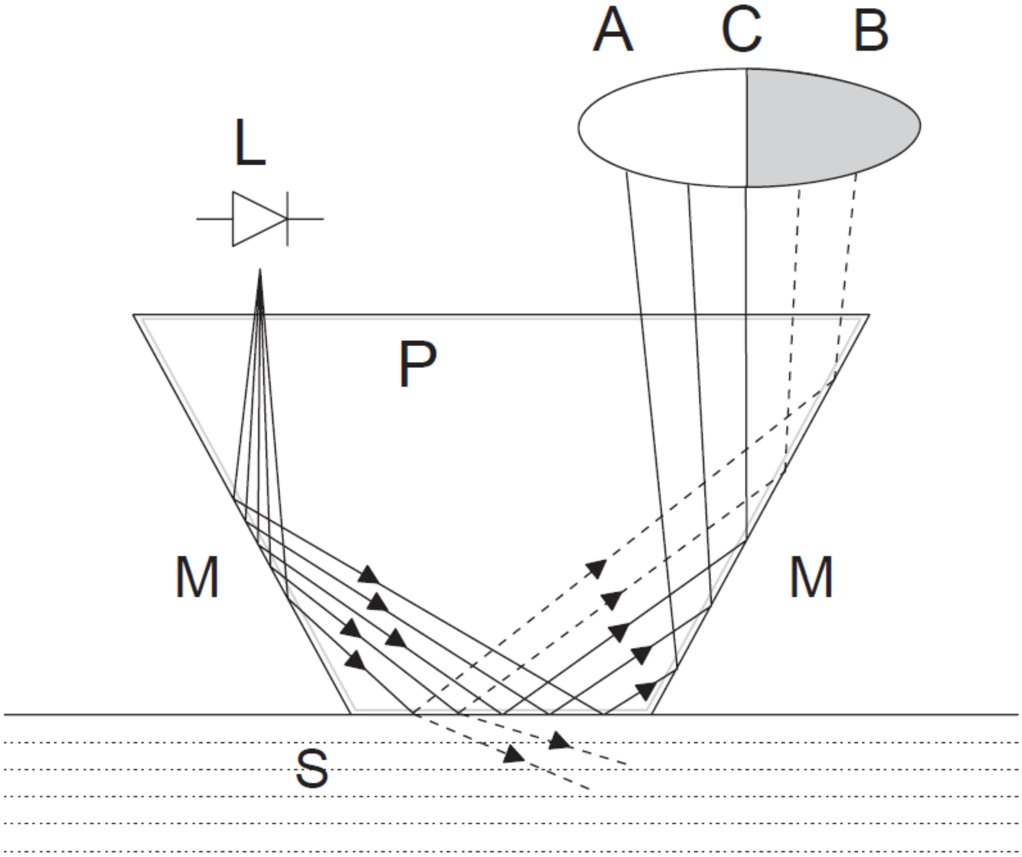


Figure 7. The principle of measuring refractive index (20)

Normally the molecular size of the dissolved solids has a significant effect on the refractive index per molecular unit. The larger the molecular size, the larger the refractive index per molecular unit. Lignin has a large molecular size which gives an accurate correlation with refractive index measured by a refractometer. Furthermore, in brown stock washing lignin presents a large share of the diluted compounds in pulp solution, affecting greatly to the measured concentration by a refractometer. This is an advantage for wash loss determination as recent investigations suggest the measurement of lignin as a wash loss indicator. (19) (21)

Kopra et al. (21) have studied the use of a refractometer as a wash loss indicator. Suggested advantages of this method include the fact that the refractive index is not influenced by particles, bubbles, fibers or color and can therefore be placed in challenging conditions, even in medium or high consistency lines. As disadvantage of the method it is suggested that the refractometer does not measure lignin adhering to the surface of fibers. Figure 8 represents concentration measured by a refractometer and consistency. From the figure it can be seen that increased lignin increases consistency measured by refractometer. On the contrary, conductivity decreases at the same time. Kopra suggest that the behavior of the conductivity could be a result of the negative charge of lignin tended to be neutralized by positive ions from the liquid.

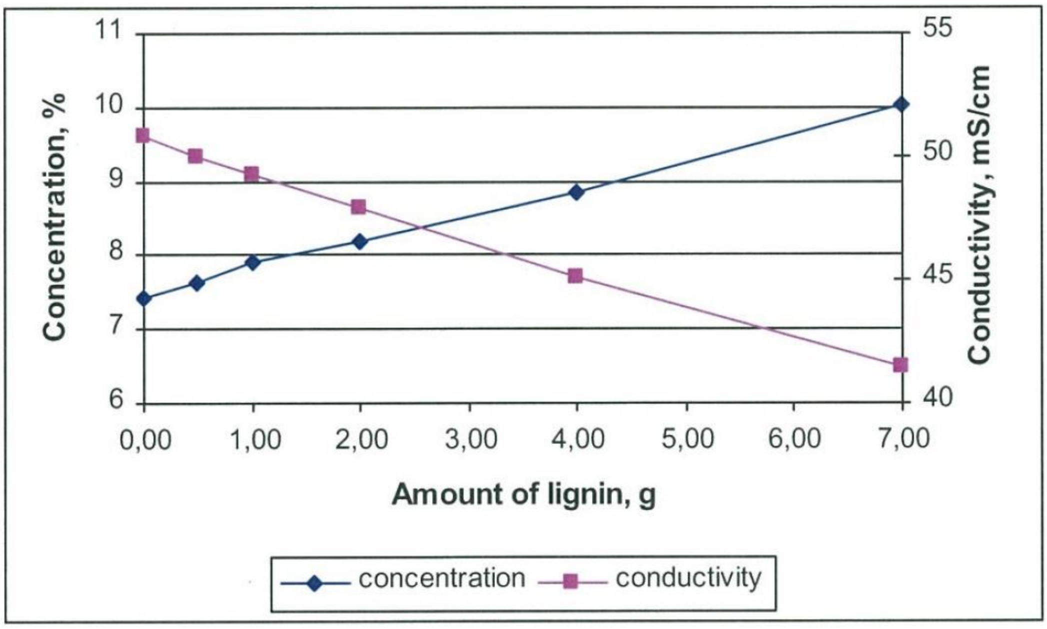


Figure 8. The effect of commercial lignin addition on concentration and conductivity in strong brown stock washing filtrates (250g). (21)

Furthermore, in concentrations used in brown stock washing, the refractometer output correlates well with COD, thus enabling the creation of a COD output. Figure 9 represents an experimental correlation of COD and concentration measured by a refractometer in a brown stock washing line (22). Another advantage of the refractometer is the wide measuring range, practically from 0 – 100 % concentration. (23)

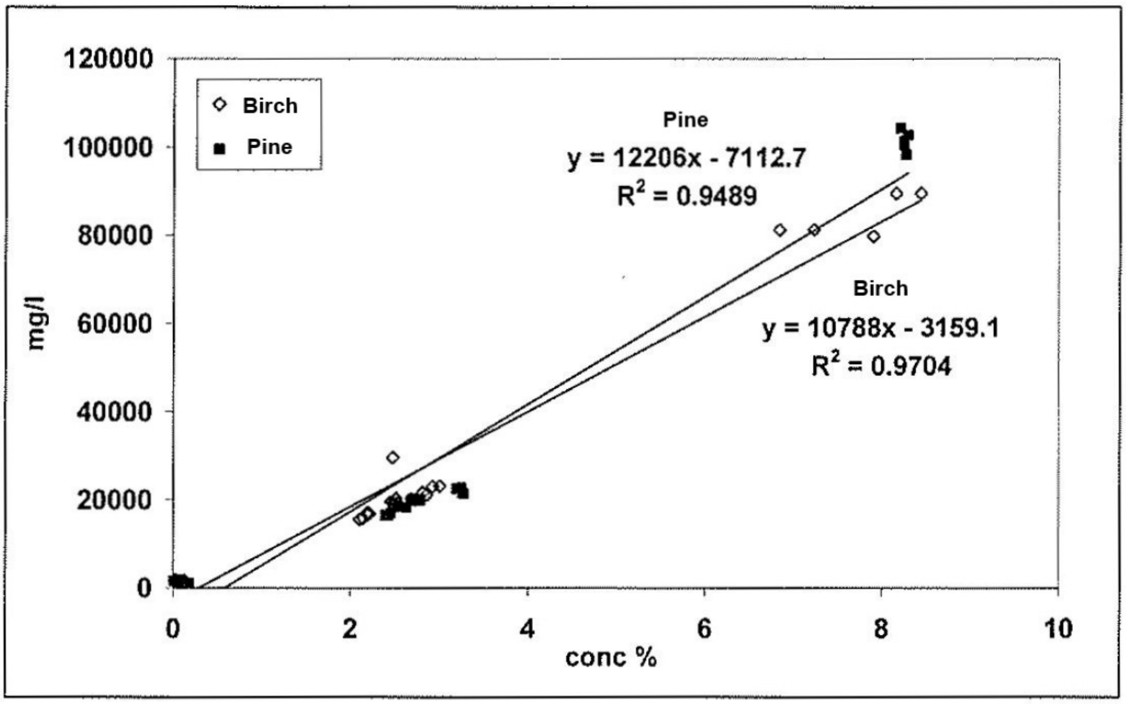


Figure 9. Experimental correlation of COD and concentration measured by a refractometer. (22)

Lignin measurement by light absorbance / transmittance

Another recent method to measure wash loss is an inline sensor utilizing the strong light absorption of the lignin molecule in the ultraviolet and visible light. A study group led by Andersson (24) *et al.* suggest that the output of the measurement is directly proportional to dissolved lignin and can be quantified as filtrate kappa number, i.e. the amount of lignin left in the filtrate. Alternatively, output can be converted to COD, which presents a significant correlation with the measurement. Light absorbance method has been used to measure lignin content before but this method, according to the study, enables the measurement in the presence of pulp fibers. This is due to a new measuring device, where the time period with fibers in the measurement can be identified and erased from the data used to calculate the light transmittance and absorbance, as illustrated in figure 10. Finally, using these values the dissolved lignin concentration is determined. A disadvantage of this method is that it cannot be used in the most important washing performance calculations, such as DR or E-value (25).

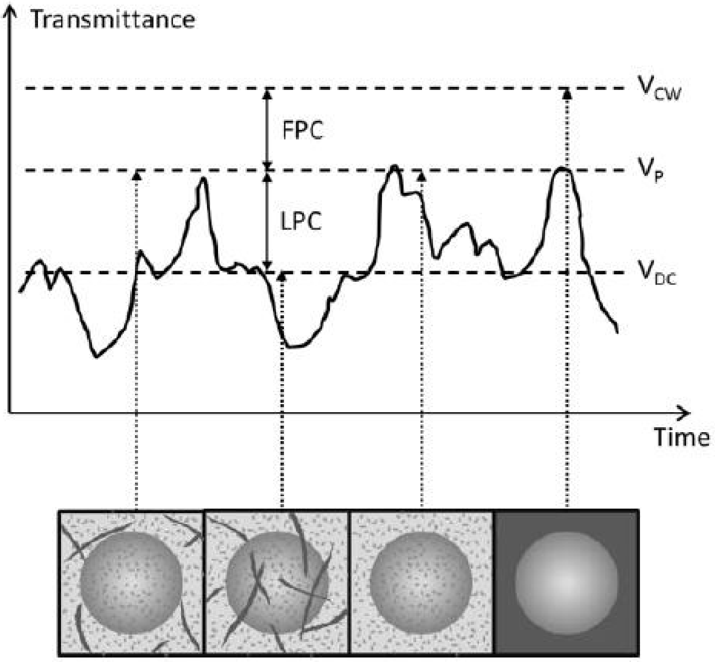


Figure 10. Principal signal extraction of dissolved lignin sensor. (24)

As illustrated in upper chart of figure 11, black liquor light absorbance weakens significantly as the wave length grows. For this reason the UV region is used in kappa number measurements, preferably at 280 nm. The inline dissolved lignin measurement utilizes higher wavelengths, where the absorption is significantly lower, but still suitable for quantitative determination, claims a study by Andersson (24). The coefficient r^2 is depicted in lower chart of figure 11. Experimental studies with this measurement have been carried out on pulp after oxygen delignification. However, more experiments should be performed to analyse the viability of the method in different concentrations. (24)

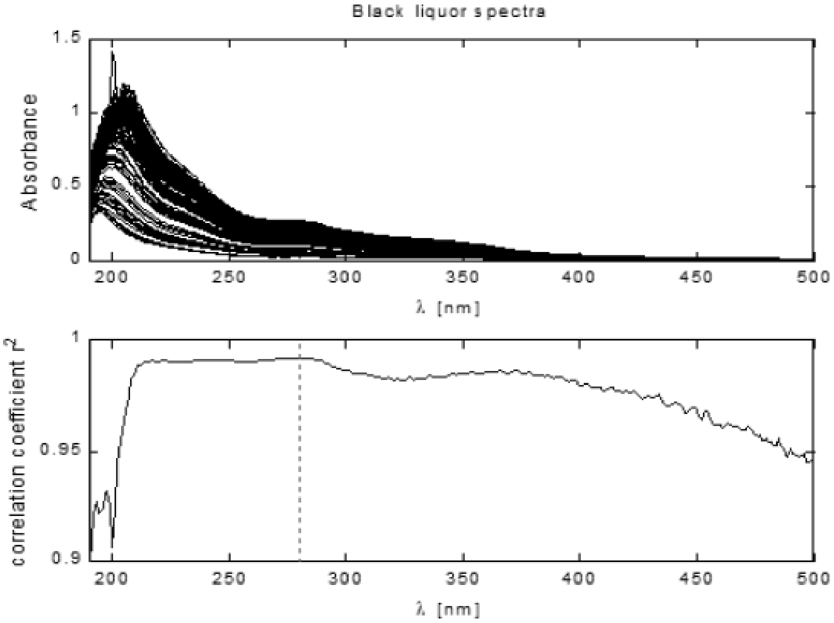


Figure 11. ***Upper***: **Spectra from black liquor samples.** ***Lower***: **Correlation coefficient between the absorbance and lignin content as a function of wavelength, λ. (26)**

3. Controlling

3.1 DD-washer

Structure and washing phases

The structure of the drum displacer (DD) is depicted in figure 12. The cylindrical surface of the rotating drum is divided in axial compartments, which act as washing stages. The bottom of the drum is made of perforated plate, enabling the black liquor to be displaced by washing liquid. Pulp is fed to the feed zone (2), at 0.2 – 0.6 bar pressure and in 4 – 10% consistency, depending on the process. A uniform pulp pad is formed in the compartment, as the liquor exists trough the perforated plates. As the drum rotates, the pulp pad enters the first washing zone separated by string powered seal bars.

In the washing zone, wash liquid is injected evenly to the pulp from the washer casing at 0.5 – 1.0 bar. Due to the pressure difference the wash liquid displaces the black liquor in pulp. DD- washer usually has 1 - 4 washing stages. After the last washing zone, excess liquid from the washed pulp pad is vacuumed and the pulp is discharged.

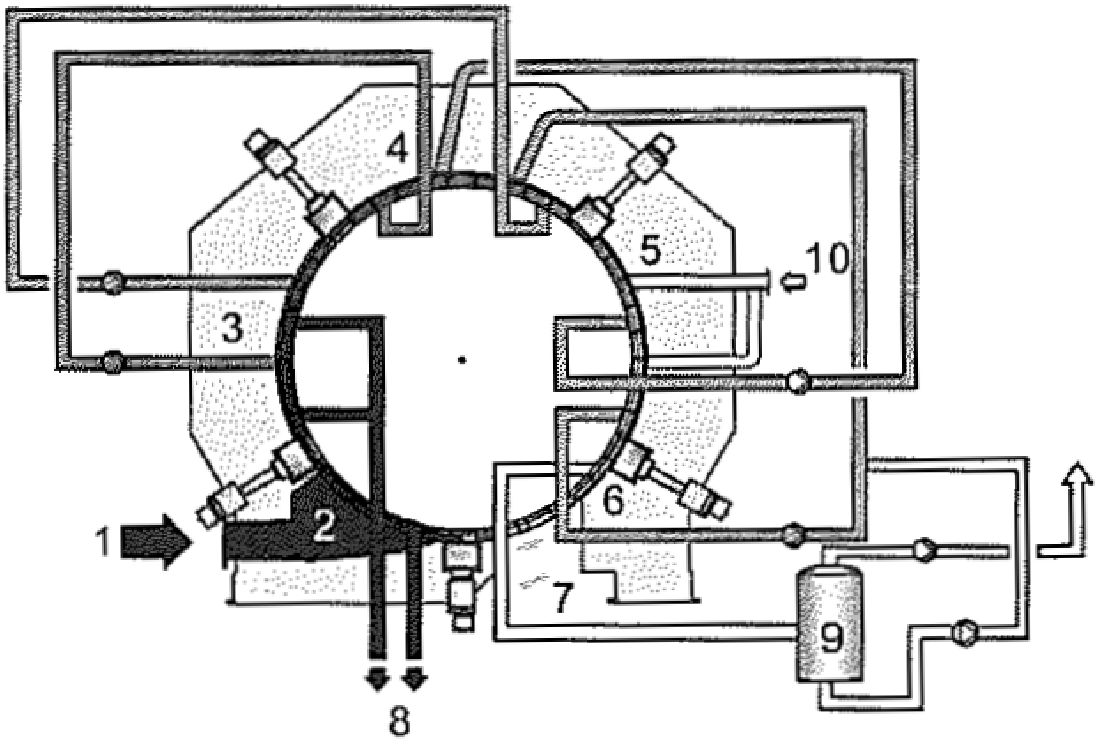


Figure 12. Three stage DD-washer: 1.Pulp inlet, 2. Formation of pulp pad, 3. First washing stage, 4. Second washing stage, 5. Third washing stage, 6. Vacuum stage, 7. Cake discharge, 8. Liquor exit, 9. Liquor from vacuum stage (vacuum container), 10. Wash liquid inlet. /Ahlstrom machinery/ (2)

Every washing stage of the drum receives washing liquid with different concentration so, that the dirtiest liquid washes the dirtiest pulp in the first stage and the cleanest liquid washes the cleanest pulp in the last stage. To illustrate the function of the different stages, COD and dry solids contents in different fractions of a two stage, three-fraction DD washer are depicted in figure 13. One drum usually contains 1-4 washing stages, giving the drum significantly higher performance than a conventional vacuum filter. (2)

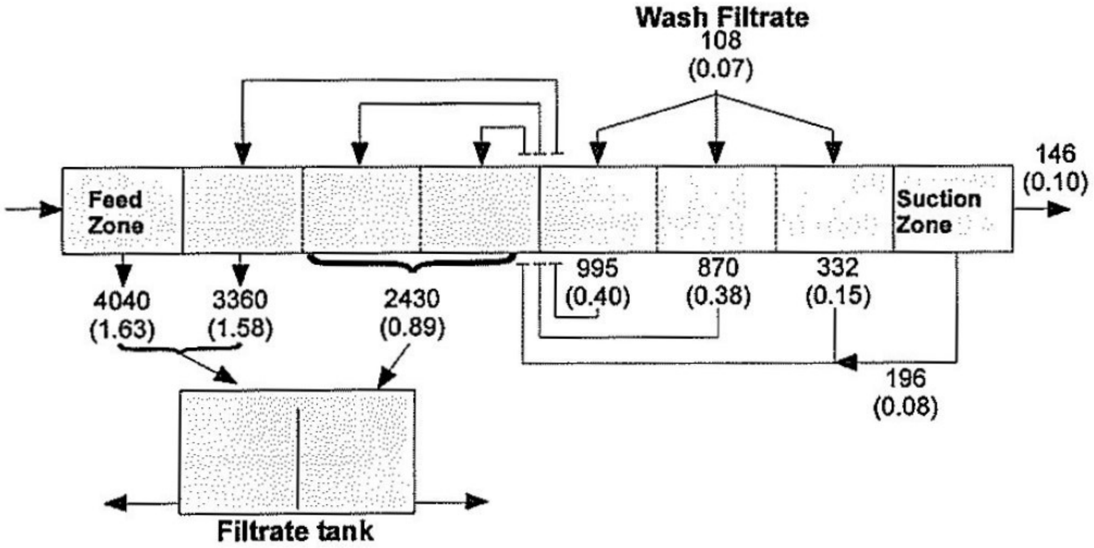


Figure 13. COD (mg/dm^3) and dissolved solids (in brackets, %) contents in different fractions of a two stage, three-fraction DD washer.

Control of DD-washer

Conventionally the DD-washer is controlled by adjusting key parameters affecting the washing process. These parameters are defined below.

In a conventional DD-washer control, operators adjust the amount of wash liquid, pulp inlet pressure and wash liquid pressure, so that these three parameters maintain a certain balanced state with desired production rate. This makes the control of the dilution factor (DF) rather tricky. The operator has to optimize many variables affecting the washing process, leaving the control of just one parameter problematic.

Due to the importance of the dilution factor there has been a need for a more sophisticated control method. There are applications utilizing feedforward from the production rate to adjust the wash water flow and a constant dilution factor. Additionally other methods for DF adjustment exist today. These will be discussed more closely in the following chapter, 3.2. (27)

Excess use of washing water should be avoided in sake of profitability, as the excess water will have to be evaporated resulting in high costs. High wash liquid consumption also raises the wash water pressure, which might result in spill over of wash liquid through seal bars. Too low wash liquid usage normally results in higher washing loss. Furthermore, runnability problems such as too high consistency of the pulp cake may occur. (28)

Conventionally**, pulp feed pressure**, adjusts the **drum rotation speed**. When the feed pressure is raised, the drum starts to rotate faster, and contrariwise. If rotation speed is too low, the pulp cake in the washer will pack too densely, which increases the wash liquid pressure. If wash liquid pressure rises above 1 bar, there is a risk that the washing liquid runs under seal bars and by-passes washing stages. Furthermore, too low rotation velocity increase drum torque in exceed, causing the drum to stop as the motor torque limit is surpassed. On the contrary, if the velocity is too high, the pulp does not have sufficient washing time in the washer, resulting in high washing loss. Moreover, with not enough time to form properly in the feed zone, the quality of the pulp cake deteriorates. Figure 14 depicts an experimental result of how displacement ratio deteriorates rapidly when feed pressure is taken under 20 kPa (29). The figure also hints that increasing the feed pressure higher than 20 kPa does not enhance displacement ratio.

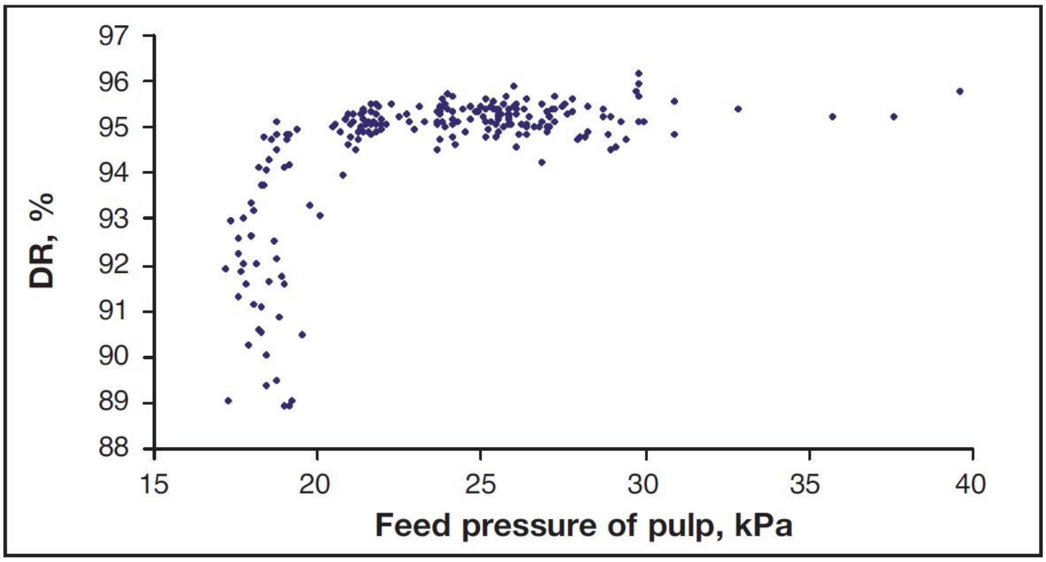


Figure 14. The effect of feed pressure on displacement ratio. (29)

Torque is used as a measurement of drum motor load. If torque is too high it has to be lowered by lowering the pulp feed pressure, which in hand increments the drum rotation velocity. Control of the DD-washer drum rotation speed using drum torque as controlled variable is an alternative to the conventional feed pressure control. Control of drum torque aims to maintain the pulp mat in a steady consistency and give a more even formation to the pulp in washing. This should in turn lead to a more constant washing result. In the approach torque is the adjustable variable, instead of conventional feed pressure. Karjalainen implemented the drum torque control in his study and reports steady control of DD-washers and a possibility to use a higher level feed pressure. (28) (30)

In one application, the drum rotation speed is adapted to production rate and fuzzy logic is utilized in the control (31). The idea of this approach is to keep the rotation speed as low as possible to achieve high washing efficiency.

Pulp feed consistency has a great effect on a DD-washer washing performance. In order to achieve an effective displacement, the pulp must form a uniform cake in the washer feed zone. Feed consistency plays an important role in the formation of the cake. If the consistency is too low, the feed flow must be boosted, which increases the feed pressure and subsequently limits production rate. Another problem with low feed consistency is the too tightly packed pulp cake, which deteriorates the washing liquid permeability. On the other hand if the consistency is too high for the washer, the pulp cake might carry air thus declining the performance. Also the formation of a uniform pulp cake may fail due to too high consistency. In this case the pulp mat is left with denser and looser spots, producing the wash liquid to pass through the loose spots and leaving the dense spots with less washing. However, for a DD-washer, it is more rare to have too high of a consistency. (13) (32)

In contemplation of washer capacity, the drum speed and inlet consistency are critical parameters. The capacity depends on both, drum speed and inlet consistency as figure 15 illustrates.

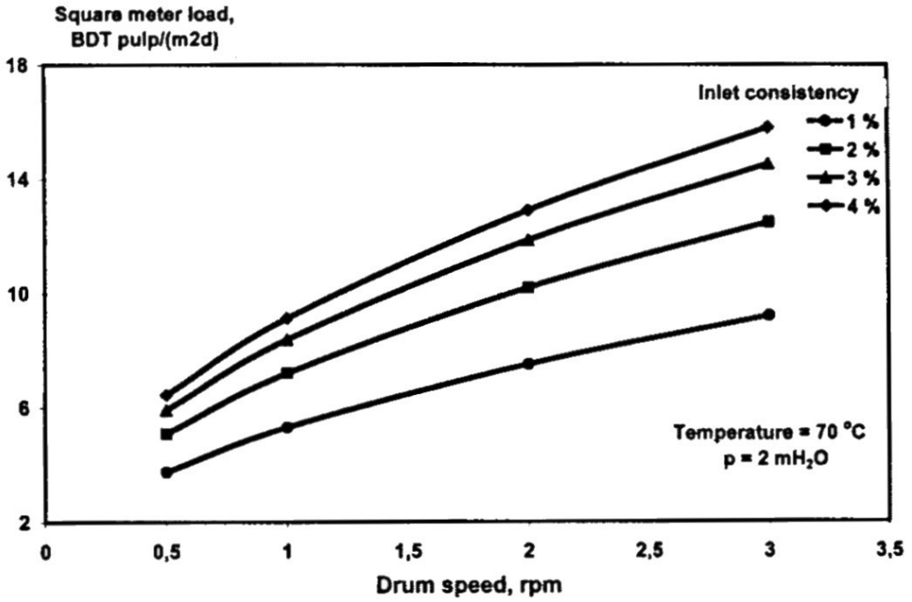


Figure 15. Effect of drum speed and inlet consistency on drum capacity. (33)

In washing, a higher outlet consistency leads to a lower washing loss and is therefore desirable. However, the correlation is not linear and the advantage of higher discharge consistency is greater at systems having lower consistencies. Table 4 shows a calculated effect of discharge consistency on soda loss. In the table soda washing loss is presented as a function of discharge consistency and a constant washing loss of 10 g/l is assumed. It can be seen that washing loss decreases as discharge consistency increases. This is due to the simple fact that there is less liquor present in higher discharge consistencies.

Table 4. Effect of discharge consistency on soda loss. A soda consistency of 10 g/l is assumed. (4)

Discharge Consistency (%)	Mass Filtrate/ Mass Fiber	Soda Loss per O.D. Ton Pulp (lb)
8	11.5	240
10	9.0	188
12	7.3	153
14	6.1	128
16	5.3	109

3.2 Washing line

Measurements

Continuous on-line measurements are essential part of the line control. It is fundamental to know the state of the process in order to control it. It can be said that if a variable cannot be measured, it cannot be controlled. Real time washing loss measurements are presented in chapter 2.3. Moreover, many other variables have to be measured in order construct a reliable and effective washing control system. These variables include flows, consistencies, tank levels, temperature and pH. However, these measurements are not discussed more closely in this paper. (31)

Soft sensors are models used to express parameters that cannot be measured directly, but have to be calculated or deduced using existing measurements as inputs. One example is production rate, which is calculated from flow when consistency is known. Soft sensors are able to provide important process data. However it should be bared in mind that measurements have certain inaccuracy and the uncertainty increases when many measurements are to obtain a soft sensor. Other soft sensors include e.g. conductivity targets, delayed consistency or rotation speed target. (34) (31)

Control of dilution factor of the washing line

As mentioned, the dilution factor is the single most important factor concerning washing efficiency. Sufficient wash water should be used to achieve low washing loss, and high pulp cleanliness, but excess water consumption deteriorates cost efficiency as the water has to be evaporated later on at the evaporation plant. Due to the countercurrent liquor flow of modern brown stock washing line, the control of dilution factor should be adjusted for the whole washing line.

There is an optimum operating point for a dilution factor, where the requirements of other departments are met so that minimum operating cost is achieved. Figure 16 represents an example of an optimum operating point of the dilution factor. From the figure it can be seen, that if the dilution factor is too high the operating costs increase due to cost associated in other departments, being mainly higher energy consumption in evaporation. On the other hand if the DF is too low, costs resulting in other departments increase again, especially in bleaching stage where more bleaching chemicals have to be used. As a result, every deviation from the optimum dilution factor results in higher operating cost. Therefore the lowest operating cost and the optimal operating conditions are achieved by always operating the plant at an optimal dilution factor.

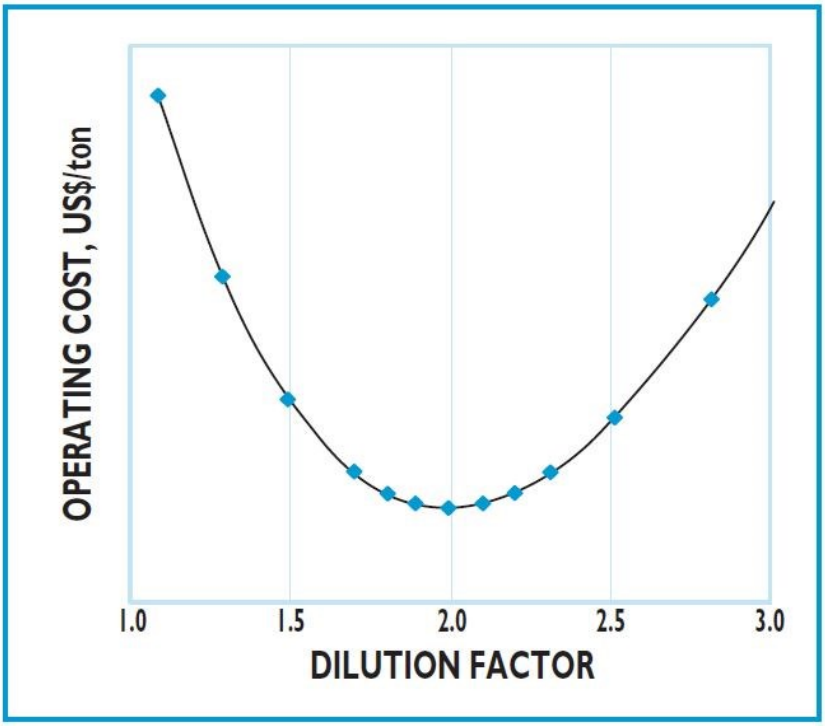


Figure 16. Example of an optimum operating point of dilution factor. (35)

The optimum DF depends on the plant equipment and the plant conditions and therefore each plant and each washing line has an individual optimum DF. If the operating conditions of the plant would be considered stable, the optimum DF would be stable as well. In this case it would be rather simple to operate the plant at optimum dilution factor by using a feedforward from production rate to maintain a constant DF. However this is not the case in practice, as the actual process conditions are in constant movement. According to Lundqvist (36) dilution factor must be correctly chosen in relation to the status of the washing equipment, the properties of the pulp, and the prevailing black liquor conditions inside the washing plant. In consequence, many control approaches have been developed to adjust the dilution factor according to the before mentioned process conditions.

Turner (37) suggests three principles for brown stock washing efficient control. These principles are described below and illustrated in figure 17.

1. Level control with a feedforward element to decouple loops in order to eliminate oscillations by changing the washing liquid flows for all washers simultaneously
2. Dilution factor control using a feedforward from production rate to maintain a constant dilution factor
3. Conductivity feedback to measure the washing quality and to correct the dilution factor

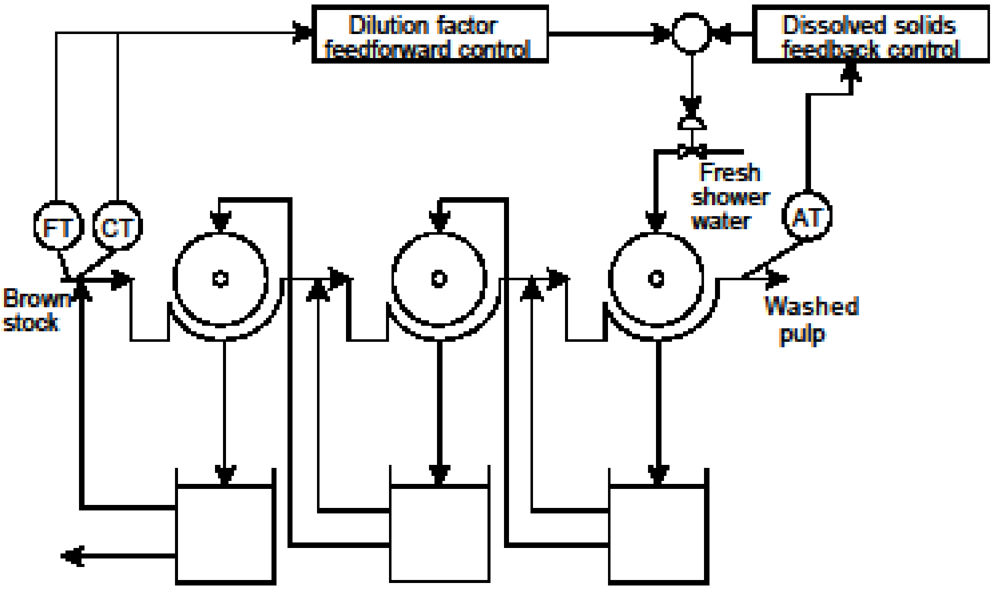


Figure 17. Control of dilution factor of the whole washing line. (38)

Bender *et al*. (39) has implemented the use of refractometer and conductivity meters to measure the solids and soda loss after the last washing stage in a four washer line. These measurements together with a model based control system resulted in 10% increase in production. Furthermore, control of defoaming agent using entrained air tester was intended, but not achieved.

Kopra (21) (40) (23) (29) has studied the use of refractometer to optimize wash water usage and to analyse the state of an individual washer or the washing line. The results claim refractive index as a reliable and useful tool to continuously monitor and control the state of washing. Furthermore, the refractometer has proved to give valuable on-line results from different stages of the washing, thus enabling the discovery of the black spots and the development of the washing line.

Rudd (41) has studied the use of neural networks as soft sensors to adjust the dilution factor. He uses the networks to express mat consistency, mat density and washing loss of the washer and to adjust the dilution factor according to these parameters. The objective is to stabilize the process and to decrease the standard deviation of black liquor solids. Results from an eight-day trial indicate a 25 % reduction in standard deviation of the black liquor solids.

Production rate changes have been found to be a common reason for disturbances in washing line. Wash water should be optimized to production rate changes to achieve the desired DF. It should be bared in mind that the production rate is a soft sensor, representing an inaccuracy of a certain degree. Usually some level of damping is required to cut off peaks in production rate. Wasik *et al*. (35) studied a dynamic control system during production rate changes. According to the study results he suggested the use of fuzzy logic in the control strategy to optimize controller response.

Control systems

Many advanced control systems to optimize brown stock washing have been introduced by different suppliers. They are all more or less based on the above mentioned criteria of production rate feedforward, washing loss feedback and tank level control. Figure 18 represents a strategy of a washing optimizer by Metso. The structure of the different washing optimizers tend to be somewhat similar, having washer specific controls and additionally an upper level control system to manage the dilution factor and washing loss of the whole washing line. Furthermore, some washing line control systems have an option to adapt the line according to requirements from other departments, e.g. evaporation plant.

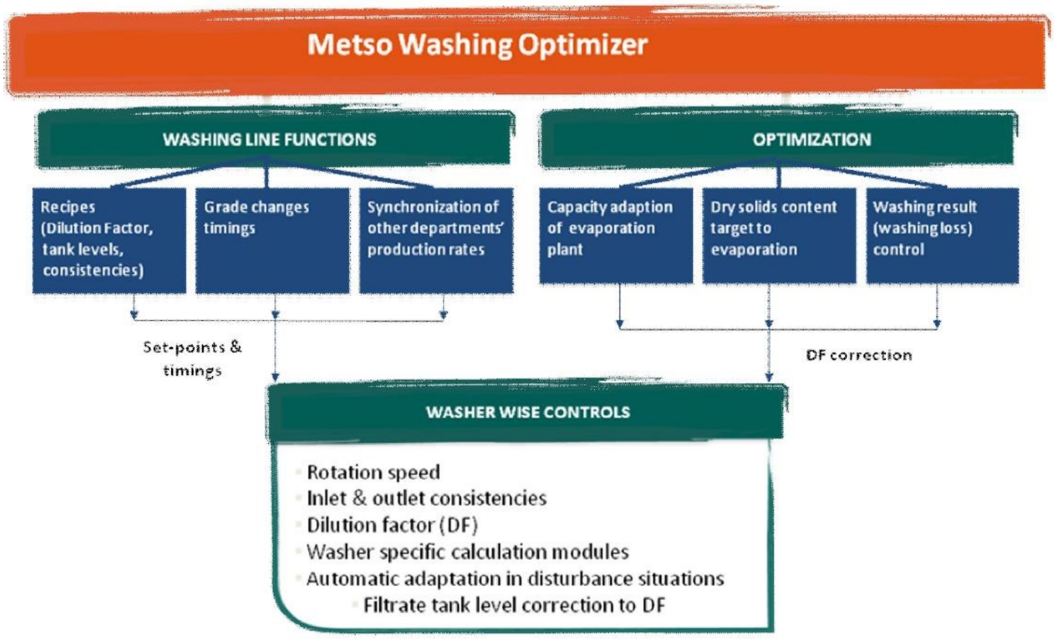


Figure 18. Strategy of a washing optimizer by Metso. (30)

Kapanen et al. (31) has studied and described the development and implementation of several brown stock washing optimization systems. The systems form from two parts; individual washer optimization and washing line control. The study results in decreased washing loss and increased discharge consistency. Furthermore, he concludes that the system makes operator's work easier and eliminates human errors. Additionally, the entire line is more tolerant to disturbances and recovers from abnormal situations more quickly and effectively.

Environmental control

Effective and controlled water usage in brown stock washing helps to control the stress caused on the environment. Dilution factor is the key parameter, from environment perspective as well. Reduced water consumption degreases the water footprint of the products. Moreover, less water to evaporation means enhancement of mill's energy balance, and degreased energy footprint of the products. On the other hand, if not enough water is used to achieve satisfactory pulp cleanliness, more bleaching chemicals have to be used resulting in higher burden on the water body. High washing loss together with high bleaching chemical consumption may also lead to the formation of notorious AOX. (13)

4. Economic analysis

Brown stock washing is one of the key areas when considering the productivity, cost effectiveness and profitability of a pulp mill. Undoubtedly, a well-controlled washing department lowers costs in other departments, thus increasing profitability of the entire mill. Another advantage of effective and optimized washing is the possibility to increase the plant production due to a steadier production rate, or/and a controlled dilution factor. When accurate control of the washing and dilution factor is achieved, the management of the mill can decide on how they best use the potential. (36)

4.1 Cost effectiveness

The changes in the washing line are strongly reflected to other departments. In fact, brown stock washing line does not comprise of many direct operational expenses. Mainly the amount of defoamer to be used can be qualified as direct cost (42). The importance of the washing to the mills economy derives from the expenses caused to other departments caused by washing result and water consumption. The greatest economic effects are created in evaporation as energy consumption, in bleaching trough bleaching chemical consumption and in chemical recovery as cooking chemical makeup. There are effects to other departments as well, which will be addressed below. (35)

As illustrated in figure 14, the optimal dilution factor provides the best economic result. As a result, an optimum dilution factor could actually be considered as the ultimate objective of brown stock washing, as pulp cleanliness and chemical recovery are embedded to the concept. Optimum DF being the objective, the means to achieve the objective are effective control and operation of the washing line, enabling a stable but flexible dilution factor in all situations.

4.2 Economic effects on other departments

To understand the cost associated with brown stock washing, it has been suggested that a curve be made on the effect of dilution factor variation on each department affected. The below addressed effects are presented as cost versus dilution factor.

Evaporation

Cost of evaporation can be calculated by:

A) Calculating the shower flow using equation 9, where S is the shower flow (l / BDt), $ø_{in}$ is consistency to washing stage and $ø_{outlet}$ is the outlet consistency of last washer. In here the assumption is made, that the shower water equals weak black liquor to evaporation plant.

B) Calculating required evaporation with equation 10, where Evap is the evaporated water / BDt, TDS_{evap} is the total dissolved solids to evaporation and ϕ_{evap} is the concentration after evaporation.

$$S = \left(\frac{1 - \phi_{in}}{\phi_{outlet}} + DF \right) * 1000 \qquad (9)$$

$$Evap = S - \frac{TDS_{evap}}{\phi_{evap}} \qquad (10)$$

Calculating steam required for the evaporation by using economy factor, which is approximately equal to the number of effects in evaporation minus 1. Calculation is done by dividing the evaporated water / BDt by the economy factor.

C) When cost of steam is known per kg, the cost per BDt is calculated simply by multiplying cost of steam by steam required. (42)

By calculating the cost with different dilution factors, a table can be created and a curve of the effect of dilution factor to the cost of evaporation can be drawn. The evaporation cost increase linearly as the washing water is increased.

Cooking chemical losses

Costs from lost cooking chemicals decrease exponentially with increasing wash water flow. When determining chemical loss in washing, a curve of dilution factor versus chemical loss can be generated empirically. This can be done by varying the last stage shower flow and measuring the salt cake or sodium loss in the pulp leaving washing stage. With the curve created, and chemical price known, the cost of cooking chemical to dilution factor can be determined. (35) (42)

Cost of bleaching chemicals usage

When evaluating the bleaching chemical consumption in relation to dilution factor, it should first be determined which chemical consumption is associated with washing efficiency. In general, these chemicals are chemicals used to oxidize and extract the black liquor solids carried into the bleach plant with the pulp. Compton (42) suggests that these are oxygen in oxygen delignification, chlorine and/or chlorine dioxide in the first bleaching stage and caustic in the second stage. Bleaching chemical costs increase exponentially with increasing wash water flow (35).

Stromberg (14) has used COD wash loss to predict the chemical consumption in chlorination bleaching stage. He resulted in 0.4-0.8 kg of active chlorine consumption to one kilogram of COD, depending on the target kappa number. Lunn (25)

A mill specific curve for bleaching chemical cost to dilution factor can be calculated by:

A) Empirically determining the washing loss for a certain dilution factor.
B) Using a constant to express the cost of chemicals per washing loss unit.

C) Calculating the cost of the chemical consumption.
D) Repeating the procedure for other dilution factors, constructing a table for bleaching chemical cost and dilution factor and drawing the curve. (42)

Cost of organic material losses

The loss of black liquor organics in washing results in less organic solids for energy production in recovery boiler. This may lead to increased need for extra fuel and thus to increased costs. Compton (42) suggest a rather complex way to calculate the organic washing loss from the soda loss based on cooking yield, active alkali application rate and causticizing activity.

Cost of heating shower water

Cost of heating shower water is much dependent on the water flows at observed mill. For example, if secondary condensate is used, it is already at rather high temperature, leaving the need for heating small. Controversially, if water is heated solely for washing, the cost will be large. The calculation to determine the cost of heating water is somewhat similar to the cost of evaporation and can be done by:

A) Calculating the shower water using equation 9
B) Calculating the heat required for the water temperature rise.
C) Calculating the steam required.
D) Calculating cost of steam at the evaporator.

Additional costs provoked by dilution factor on the washing line include costs of secondary condensate usage and costs in waste treatment in form of nutrient chemical cost.

Comparison of costs

Compton (42) has made example calculations on the effect of dilution factor. Figure 19 represents these examples on a DF of 1.5 m^3/BDt. The example serves to give an idea of what might the costs be in relation to each other, but is not to be taken as a guideline. Operational differences and effect of DF to costs change largely between different plants. The notable factor is that the largest costs are situated in bleaching, evaporation and cooking chemical recovery. This is in correlation with other references e.g. Wasik et al. (35).

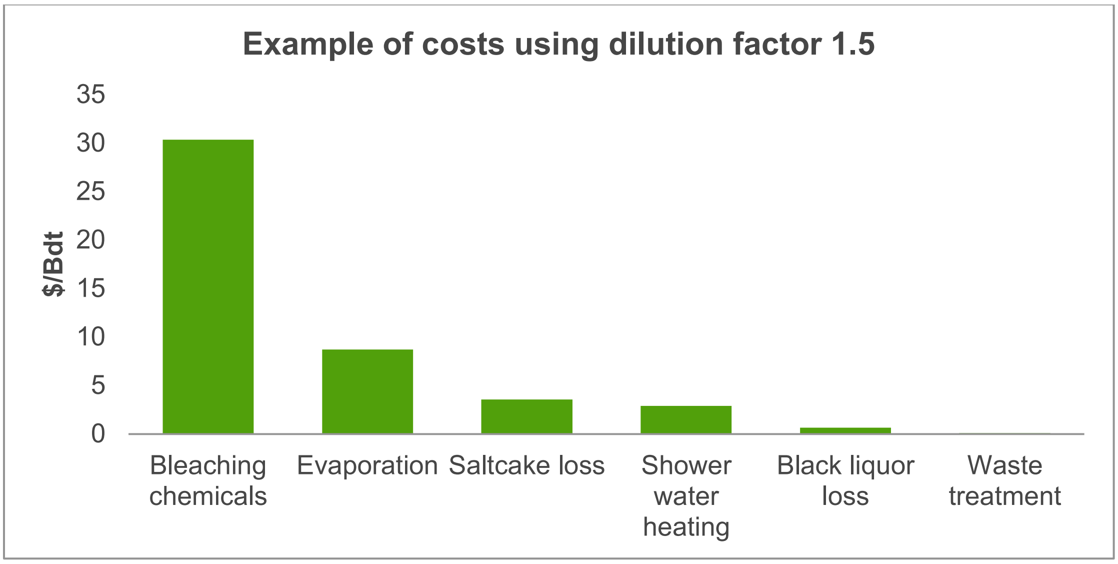


Figure 19. Example of an effect of dilution factor 1.5 on costs on different departments. (42)

4.3 Investment decision

Optimization of a brown stock washing line usually contains capital costs, which depend on the required new equipment and implementation costs, in term of mounting and maybe consulting and engineering services. When considering the feasibility of an optimization project, the most important factor is its profitability in terms of return on investment. The return on investment (ROI) is always done before the investment decision and implies the ratio of profits in relation to capital invested. Equation 11 illustrates the relationship of these factors. (43)

$$ROI = \frac{profit}{investment} \tag{11}$$

In comparison to the cash flow of an average pulp mill, the investment cost to carry out a brown stock optimization project is medium or small. Thus the investment can probably be realized without a need of capital from outside the company.

In order to calculate the ROI, the expected profits and capital investment have to be defined first. In a washing optimization project the expected profits can be calculated by summing up the savings generated by effective control of dilution factor. These savings come mainly from decreased evaporation steam consumption, decreased bleaching chemical consumption and increased chemical recovery rate. Additional savings occur in other departments as presented in previous chapter. These savings can be taken into account, if their significance and reliability are seen as sufficient. More profits expectance may come from the option to increase production rate, but this is largely case dependent. Investment costs are calculated by summing up the costs of purchased equipment, engineering, instrumentation and management. (43)

Payback period is another figure to analyse the feasibility of the investment. The factor is calculated using equation 12, where investment is the total investment cost and net cash flow is the increased cash flow (44).

$$\text{Payback Period} = \frac{\text{investment}}{\text{net cash flow}} \tag{12}$$

5. Summary of literature review

Brown stock washing has an increasingly important role in the chemical pulping industry, as the environmental concerns have become a more important factor. In order to meet the increasingly strict regulations, production facilities have a need to control the wash loss from brown stock washing line to bleaching. Many strategies to control and measure wash loss have been introduces to washing lines during last decades. The literature claims the new control strategies have given pulp washing lines more efficiency and accuracy.

From the economic point of view, the costs saving potential of washing process has become more viable, as the control strategies have evolved. A steadier and more flexible control of dilution factor can optimize the water usage of the line so that each fibre is washed with the same amount of washing liquid. This is essential for the cost effectiveness of other departments. When dilution factor is optimized, the washing loss to bleaching stage is controlled and the need for evaporation is maintained at low level.

Washing loss determination is essential for the control of the line and the conventional laboratory methods are the solid ground for the determination. However, during last years the need for accurate on-line measurements has emerged due to the development of more sophisticated control strategies and the need to control more accurately the organic substances going to bleaching. Recent studies using a refractometer propose good results of washing loss determination and analysis of washing. There have been several applications utilizing online washing loss measurement and an advanced, multilevel control system.

There is no one solution on washing line optimization, since the optimal dilution factor and operation parameters are always mill-specific. The most important advantage of a control system and precise measuring devices is the possibility to obtain desired results in a mill, let it be enhanced cost effectiveness, environmental control, quality, or all of them.

6. Objectives of experimental part

The present study had two main objectives. First objective was to effectively put into service the upper level control system and the 7 refractometers on the washing line. The performance of the investment was observed in terms of wash loss and concentration of liquor leaving the washing line.

The second objective was to find the optimum values for operation parameters so that the washing line could be operated in an economically and environmentally sustainable manner. The parameter values, such as dilution factor, drum torque and feed consistency were investigated in trials carried out during one month.

Furthermore, the economic viability of the investment on upper level control system and refractometers was studied. In addition, a comparison of the on-line wash loss measurements, i.e. conductivity and total dissolved solids measurement by refractometer.

7. Introduction to pulp mill

Kaukas pulp mill is part of the Kaukas integrate, located in Eastern Finland in Lappeenranta. The integrate produces pulp, coated mechanical paper, timber products and biodiesel.

The pulp mill has two fiber lines with a total capacity of 700 000 ADt/a of bleached pulp. Fiber line 1 produces hardwood pulp with a capacity of 300 000 ADt/a. Fiber line 2 has a capacity of 400 000 ADt/a of softwood pulp.

The pulp is cooked in 12 Super-Batch digesters, four of which produce hardwood pulp and eight softwood pulp. In addition, there is a sawdust digester producing pulp for the hardwood line.

Brown stock washing line 1

The brown stock washing line consists of three DD washers, a vacuum washer and two phase oxygen delignification. After the blow pulp tower the pulp is taken to a precipitator which raises and evens out the consistency before the washers. Two parallel DD washers follow the precipitator. The DD washers are both four-stage washers, but they differ some in structure and size. From the DD washers the pulp is taken to a 2-stage oxygen delignification taking approximately 80 minutes. After the oxygen delignification the pulp moves to a two-stage DD washer. Sulphuric acid is added to the pulp after it leaved the DD-washers and the pulp is taken to a tower functioning as A-stage. After the A-stage the pulp runs through screening. The screening is followed by a vacuum washer, which has its own wash water circulation. Figure 20 illustrates the structure of fiber line 1, where the upper part represents brown stock washing line and lower part depicts bleaching line.

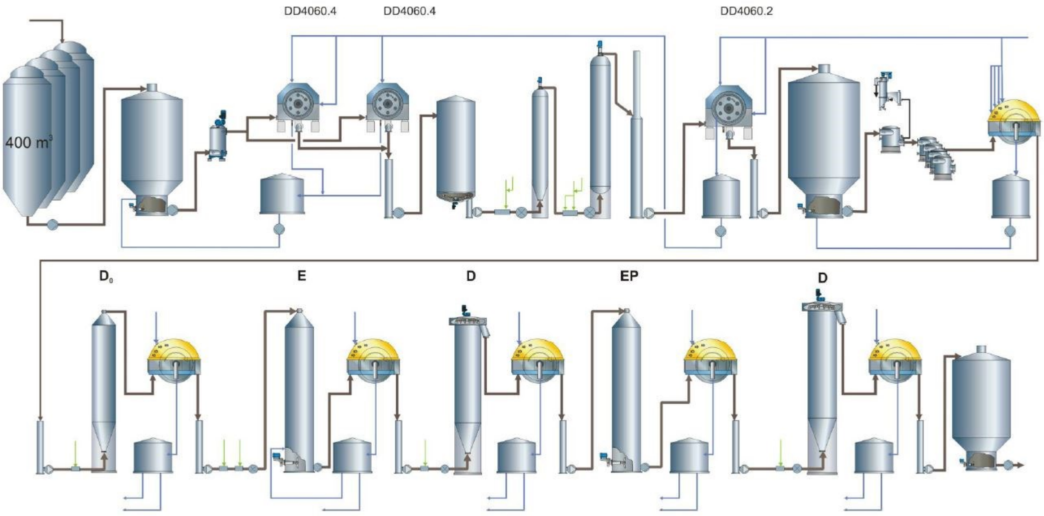


Figure 20. Fiber line 1

8. Materials and methods

8.1 Refractometers

A total of 8 refractometers were installed in the washing line to measure real time dissolved solids. The refractometers were supplied by K-patents Oy. Seven of the refractometers were model PR-23-SD and one was model PR-23-A. Four of the refractometers were installed in pulp lines and four in liquor lines. Figure 21 represent the installation sites of the refractometers in the washing line and table 4 defines the sites in more detail.

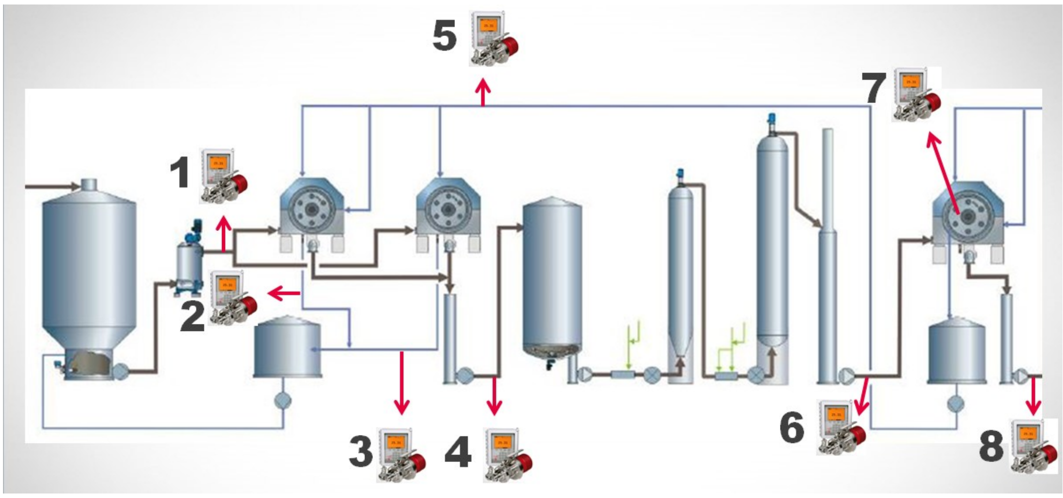


Figure 21. Installation sites of the refractometers at the brown stock washing line.

Table 4. Installation sites of the refractometers.

Installation site	Number
DD1 & DD2, pulp in	1
DD1, wash filtrate	2
DD2, wash filtrate	3
DD1 & DD2, pulp out	4
DD3, pulp in	5
DD3, wash filtrate	6
DD3, wash liquor from vacuum tank	7
DD3, pulp out	8

Three PR-23 refractometers in liquor lines had “Safe Drive” installation valves with steam wash to keep the prism clean. The Safe Drive also enabled safe removal of the sensor during normal operation, which proved to be useful during the introduction period. Figure 20 represents the installation of the PR-23-SD refractometer in filtrate leaving DD3. In addition one PR-23-A measurement was installed in a liquor line. This installation did not have steam wash, but instead a flow cell and adjustable valves to keep the flow speed high enough to keep the prism clean. Figure 22 represents the installation of this refractometer.

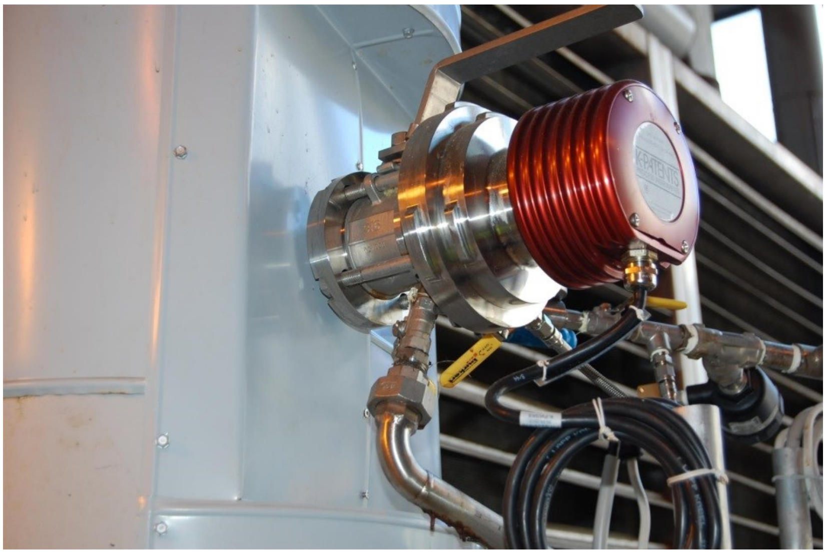


Figure 22. Installation of the PR-23-SD refractometer in filtrate line of DD3.

The four refractometers installed in pulp lines were with solid installation valves, because the flow of the fibers will keep the prisms clean. Figure 23 represents the installation of a solid valve PR-23 refractometer.

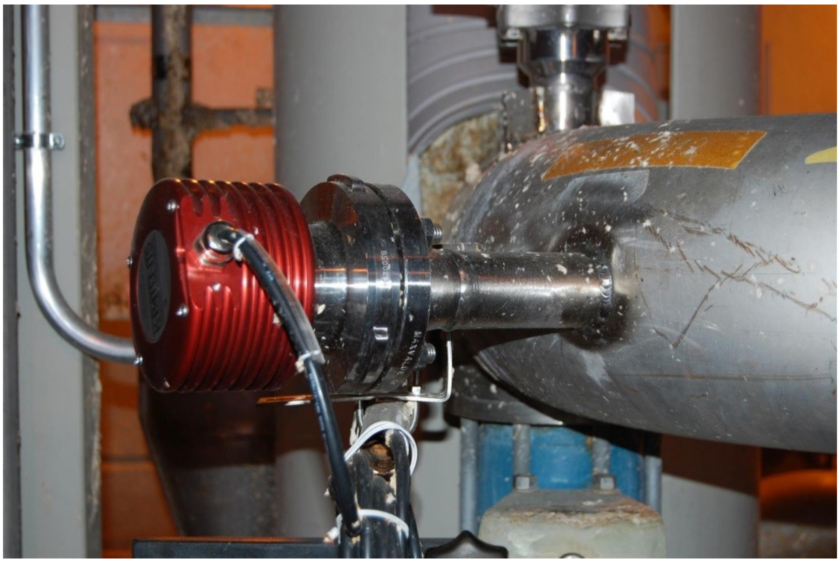


Figure 23. Installation of the PR-23 refractometer in feed pulp line of DD3.

The deployment of the refractometer number 8 did not succeed due to the fact that sulfuric acid was added to the MC pump just before the measuring installation site of the set point. The sulfuric acid affects greatly the refractometers measurement result because the portion of the dissolved solids from the added sulfuric acid to total dissolved solids of the liquor is large, about 50% or more. To compensate the effect of sulfuric acid to the measurement a calculation was created to reduce the amount of dissolved solids caused by the sulfuric acid to the measurement of total solids. The compensation was not successful due to unpredictable rapid changes in the flow of the sulfuric acid.

To replace the refractometer number 8 and obtain real time measurement of the total wash loss of the washing line, another refractometer (7) was installed on the wash liquor line leaving the vacuum tank of DD3. According to the samples analyzed in laboratory, this location gives approximately 10-20 percent higher wash loss compared to the TDS of pulp leaving DD3.

Furthermore, the existing measurements in the washing line were also used to evaluate the performance and efficiency of the washing. Used measurements included flow meters, consistency transmitters and conductivity meters. Figure 24 illustrates the existing sites for on-line conductivity measurements. All of the three conductivity measurements are located in the liquor line leaving vacuum tank.

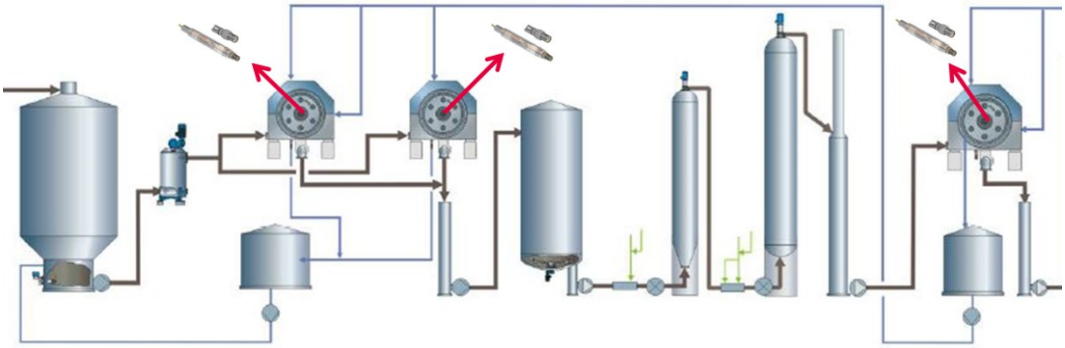


Figure 24. Installation sites of the conductivity meters in brown stock washing line.

8.2 Upper level control system

The upper level control system was put into service in co-operation with the system provider. The control system had two principal functions; the dilution factor control and the DD washer drum rotation speed control.

Conventionally the DD washers have been fed the amount of wash liquor seen appropriate. DD1 and DD2 have been perceived to require more wash liquor than DD3 in order provide an appropriate washing result. The higher consumption of wash liquor for pre O2 washing had led to the constant bypassing of DD3 washer. As the bypass valve provides the extra water to the washing line, the total dilution factor of the line has not been controlled.

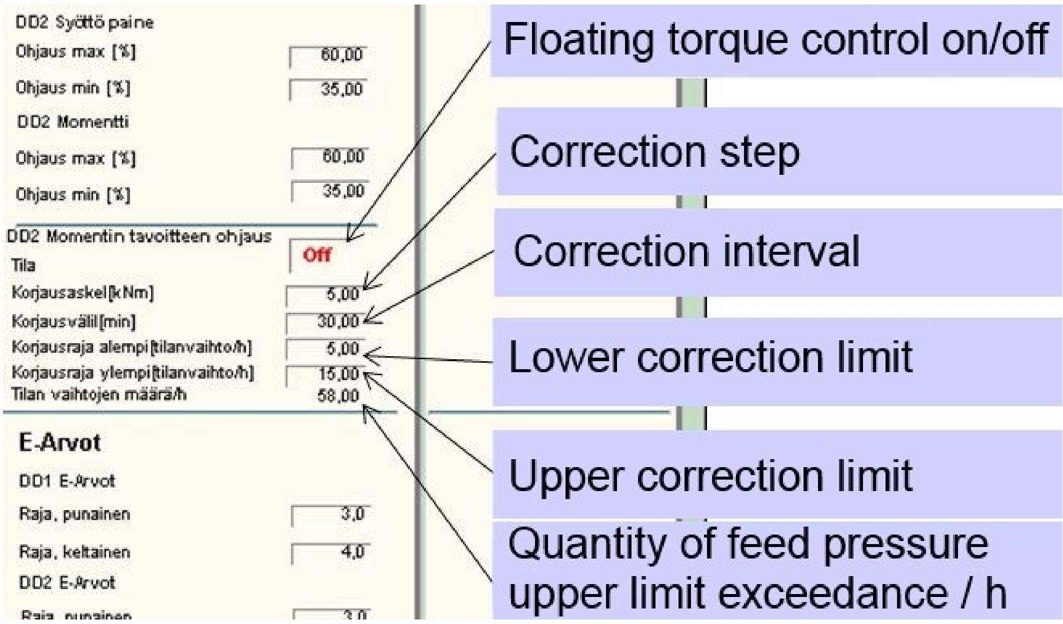
The dilution factor control of the upper level control system was constructed so that the dilution factor of DD3 controls the dilution factor of the whole washing line. This means that in a normal operation the wash liquor circle of the line would be closed and the DD3 bypass valve and the wash liquor storage emptying valve would remain closed. Hence, all the wash water entering the washing line would be utilized in DD3, enabling a higher dilution ratio for the washer and enhancing the efficiency of the line.

The target for the dilution factor of the whole washing line was given by operators. A feed forward from production rate to wash water feed in DD3 was used to maintain the dilution factor steady, while the dilution factors of pre O2 washers i.e. DD1 and DD2 were determined by the wash liquor balance of DD3 wash liquor tank. A feedback was used to tune the dilution factor of the line according to the stage and condition of the line. The feedback for the dilution factor consisted of liquor balance, dissolved solids and conductivity. Refractometers measuring dissolved solids gave feedback to the dilution factor control in real-time, while conductivity measurements were averaged.

The DD washers' drum rotation speed was based on torque control instead of conventional feed pressure control. According to the theory, the control of drum torque could be able to maintain the pulp mat in a steady consistency and give a more even formation to the pulp in washer. This should in turn lead to a more constant washing result. The torque control was constructed so, that the operators set the set point for torque and the drum rotation speed was adjusted to keep the torque constant. Feed pressure was configured an upper limit. If this limit was exceeded, the control would automatically change the controlling parameter from torque to feed pressure and lower the feed pressure to a desired level. After the feed pressure was under the desired limit the control started to control the torque anew.

The drum torque seemed to work well, but a problem occurred calling for enhancement of the control. The drainability properties of the pulp might change greatly due to change in raw material quality or cooking conditions. If the drum torque is kept constant and the drainability of the pulp changes, the feed pressure could change dramatically. During the testing period it was somewhat common for the feed pressure to drop to an inadequate level, deteriorating rapidly the wash result. If the pulp had good drainability, the torque could have been significantly higher than it was set by the set point. This problem was addressed creating a floating set point for the drum torque.

The idea of the floating set point was that the set point was automatically adjusted to the optimum level, depending on the pulp properties. The floating set point was created by first creating a calculator to keep count of the times per hour the feed pressure exceeds the set upper limit. Then a lower limit and an upper limit were set for the times the feed pressure exceeds the limit per hour. If the times of exceedance per hour exceed the upper limit, the torque set point was automatically decreased a certain amount. On the other hand, if the times of feed pressure exceedance per hour fell under the lower limit, the torque set point was automatically increased a certain amount. Figure 25 illustrates the function of the floating torque set point.



DD2 Syöttö paine

Ohjaus max [%] 60,00

Ohjaus min [%] 35,00

DD2 Momentti

Ohjaus max [%] 60,00

Ohjaus min [%] 35,00

DD2 Momentin tavoitteen ohjaus

Tila Off

Korjausaskel[kNm] 5,00

Korjausvälil[min] 30,00

Korjausraja alempi[tilanvaihto/h] 5,00

Korjausraja ylempi[tilanvaihto/h] 15,00

Tilan vaihtojen määrä/h 58,00

E-Arvot

DD1 E-Arvot

Raja, punainen 3,0

Raja, keltainen 4,0

DD2 E-Arvot

Raja, punainen 3,0

Floating torque control on/off

Correction step

Correction interval

Lower correction limit

Upper correction limit

Quantity of feed pressure upper limit exceedance / h

Figure 25. A screen capture of the configuration of the floating torque setpoint.

The result of the floating torque set point was a significant enhancement of the steadiness of the line, especially during process changes. However, sometimes the pulp drainability changed very rapidly and the floating torque set point could not react with sufficient promptness, causing the feed pressure to drop to an inadequate level. To address this problem, a lower limit for feed pressure was set up. The lower limit of the feed pressure worked in the same manner as the upper limit, changing controlling parameter from torque to feed pressure and raising the feed pressure to an adequate level.

8.3 Analyses

The analyses were performed in laboratory according to table 5. Analyses were made during the calibration of the refractometers as well as on the definition of the chemical situation of the washing line.

Table 5. Analyses carried out in laboratory

Variable	Method
Total dissolved solids, standard	SFS 3008 (105 °C)
Total dissolved solids, refractometer	See description [1]
Conductivity	SFS EN27888
Consistency	SCAN - C17:64
Sodium	SCAN - C30:73
COD pulp	SCAN - CM 45:91
COD liquor	See description [2]
Total Organic Carbon	SFS - 1484EN

1 Some TDS analyses were made using a laboratory device provided by K-Patents. The device was used as a quick analyzing tool to see the difference of an operational change performed in the line. However, all the results presented in this paper have been made using the standard procedure SFS 3008.

2 COD liquor samples were filtrated by a 10 µm paper and then analyzed in a COD analyzer as descripted in SCAN – CM 45:91

The refractometers were calibrated in co-operation with the refractometer supplier. The calibration was performed by taking liquor sample from the refractometer installation site and analyzing the total dissolved solids in laboratory. When the installation site was in a pulp line the liquor was squeezed out in less than five minutes after sampling. After 5 laboratory samples were carried out, the refractometers were calibrated to match the laboratory values. During the following months more TDS laboratory analyses were carried out and the calibration of the refractometers was fine-tuned respectively.

In addition, conductivity and liquor COD analyses were made from the refractometer installation sites during the calibration.

The pulp COD was taken from DD3 cake discharge, where the total COD wash loss was determined. The COD samples were analyzed 3 to 4 times a day during washing line trials. Consistency was determined from the cake discharge of each DD washer.

The performance parameters were created in DNA operation system. The E-value was calculated as E_{APE}-value for each three DD-washers using the equation 7 and placed on the upper level control monitor. Furthermore, traffic lights were placed on the monitor screen next to the E_{APE}-value to indicate whether the washer efficiency was poor, adequate or excellent. Figure 26 demonstrates the efficiency traffic lights in the monitor screen.

DD1 Laimennuskerroin
On 3,83 m3/ADt
C 3,60
A 46,6 l/s
DF 3,78 m3/t
E-Arvo 5,2
On Mom.
0,6 rpm

DD2 Laimennuskerroin
On 3,20 m3/ADt
C 3,20
A 47,5 l/s
DF 3,25 m3/t
E-Arvo 5,1
On Mom.
0,6 rpm

DD3 Laimennuskerroin
On 2,22 m3/ADt
C 2,12
A 74,3 l/s
DF 2,22 m3/t
E-Arvo 4,9
On Mom.
1,1 rpm

Figure 26. The E-value and the efficiency traffic lights on the operation monitor of the upper level control.

Displacement ratio was calculated using equation 4 and the calculation was introduced to the DNA operation system. The DR was not placed on the operation monitor because it was thought to offer too much information on one screen and confuse more than actually assist. Instead it was left to gather data in the system to be utilized in investigation and problem solving situations.

8.4 Trial runs

During the trials there were no significant changes in raw material composition, since the fiber line 1 is used solely to produce hardwood pulp with mainly birch as wood species. In addition, the percentage of pulp from saw dust digester was kept as constant as possible during the trials. The washing result of the washing line was determined from the pulp discharge of DD3 using different wash loss definition methods. In addition, refractometers were continuously measuring the total dissolved solids and conductivity meters were measuring the conductivity of wash filtrate from each DD-washer.

After the upper level control system and the most important refractometers for the control were put into service the performance of the created upper level control system with refractometers was tested. In the trial the line was first operated two weeks in conventional way and then two weeks with the upper level control system in function. The objective of the trial was to define the **total effect of the investment** in terms of wash loss and concentration of wash filtrate leaving the washing line.

The effect of **dilution factor** on wash loss and chemical consumption in bleaching was tested in a three week trial. The dilution factor was first raised to 4.5, then after the first week it was lowered to 4 and for the third week to 3.5. The objective was to determine the optimal dilution factor for the washing line and to clarify the effect of different levels of dilution factor to wash loss.

The effect of **production rate** on wash loss was examined by first lowering the rate to minimum operation, then raising it to normal level and at last incrementing the rate to maximum production. In addition, it was interesting to see how high production rate could be achieved and how would the line perform in maximum production.

Another trial was carried out to study the effect of DD1 and DD2 **feed consistency** on wash loss. The feed consistency was first lowered to 4.3%, then raised to 5% and at last to 5.7%. The consistency was first changed before equalization tank, after half an hour from the pulp entering the pre-precipitator and the pulp leaving the pre-precipitator, which is the feed consistency to DD1 and DD2 washers.

When operating the washers using drum torque control, the effect of **drum torque** on wash loss was studied by raising the torque first as high as the feed pressure limit allows and then step by step lowering it. The objective was to find out how wash loss is affected by torque both in low and high ends of the torque scale.

The comparison of viability and effectiveness of on-line measurement methods, namely conductivity meters and TDS by refractometer, was planned to be tested in a trial. The comparison would have been made in terms of wash loss and concentration of wash liquor leaving the washing line. However, the comparison would have needed a long trial to have reliable results and was not possible inside the time frame of this study.

The effect of dilution factor on bleaching chemicals consumption and cost was planned to be tested during the trials. Unfortunately the washing line experienced serious disturbances during the trials and there was no significant results obtained.

9 Results and discussion

9.1 Composition of liquors

Total Organic Carbon (TOC) analysis was used to analyze the organic content of liquors. To determine the organic and inorganic portions of the liquors the inorganic content was calculated as the difference. Figure 27 depicts the organic/inorganic composition of liquors from different parts of the washing line. Results indicate that the organic portion is larger in stronger liquors and smaller in weaker liquors. This is due to the fact that inorganic matter, largely composed of sodium and other smaller molecular size substances washes off more easily than organic matter such as lignin.

Liquor in pulp solution leaving DD3 has significantly higher portion of organic matter than other liquors. The reason for this is the low concentration of the liquor (~0.1 %) which in this stage is mostly washing liquid, i.e. secondary condensate containing almost solely organic matter. The liquor in pulp solution to bleaching has a large inorganic portion because of sulfuric acid added to the pulp discharge.

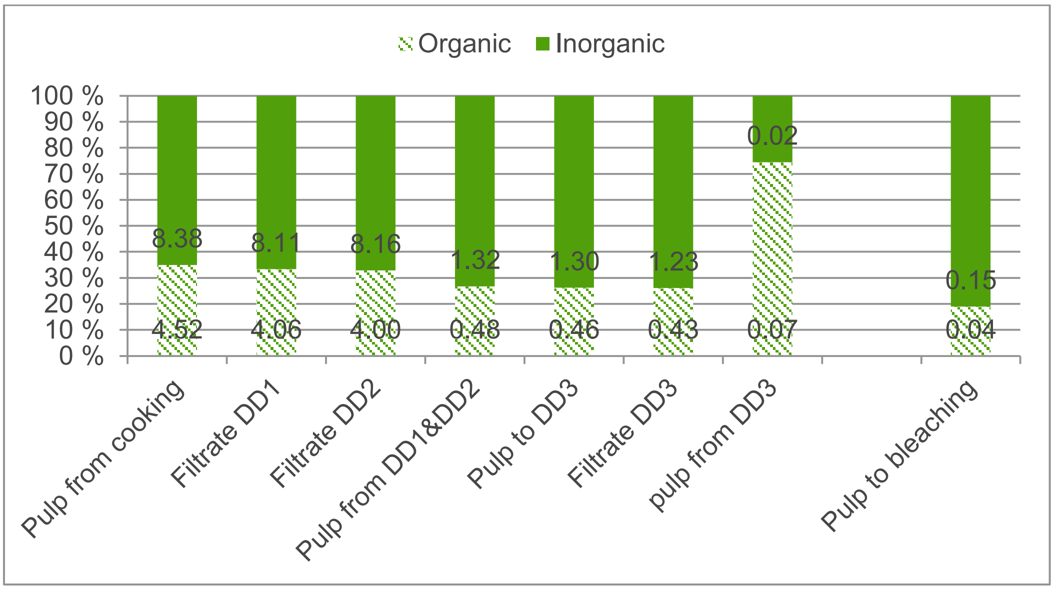


Figure 27. Composition of organic and inorganic compounds of liquor from different parts of washing line. Figures on the columns are weight percent of total dissolved solids.

Figure 28 illustrates the difference of different wash loss measurements used in the washing line. In each measuring point the conductivity and COD values were divided by the concentration of the liquor. Concentration is taken as a reference to conductivity and COD, because it represents the total amount of all dissolved solids in a solution.

When comparing figures 27 and 28 it can be seen that the COD expresses clearly the organic amount of liquor. On the other hand the result suggests that conductivity expresses more the inorganic portion of the liquor, as discussed in the literature review. Pulp from DD3 has a high ratio of COD/TDS due to the COD and low dissolved solids in the secondary condensate used as washing liquid. Pulp to bleaching contains high portion of sulfuric acid, which can be seen as a peak in the ratio of conductivity to TDS and low ratio of COD to TDS.

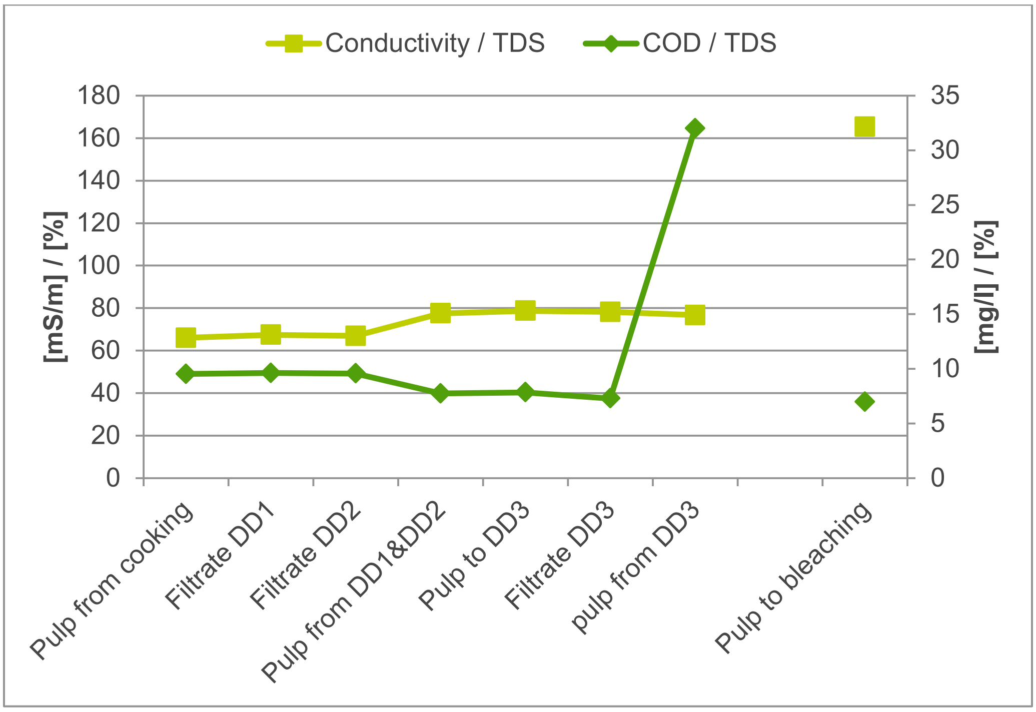


Figure 28. Ratios of Conductivity and COD to Total dissolved solids from different parts of the washing line.

9.2 Wash loss determination

Figures 29 and 30 represent the correlation of TDS to COD and conductivity to COD in brown stock washing line concentrations. Both correlation coefficients are high due to the wide concentration scale (0 – 14%). Nevertheless, the total dissolved solids measurement had a stronger correlation with COD. The stronger correlation of TDS suggests that TDS has a stronger correlation with conductivity when describing the organic matter content of liquor in pulp washing. The higher variation in conductivity measurement compared to TDS is believed to be the result of temperature and pH, which affect conductivity and thus might deteriorate the reliability of the measurement.

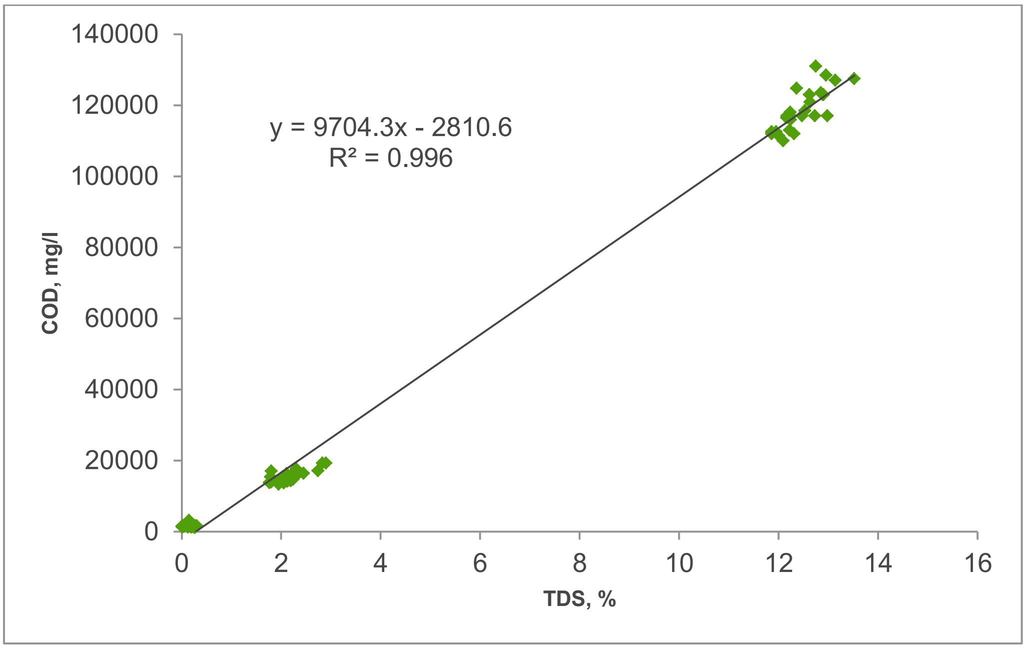


Figure 29. Correlation between TDS and COD, both analyzed in laboratory.

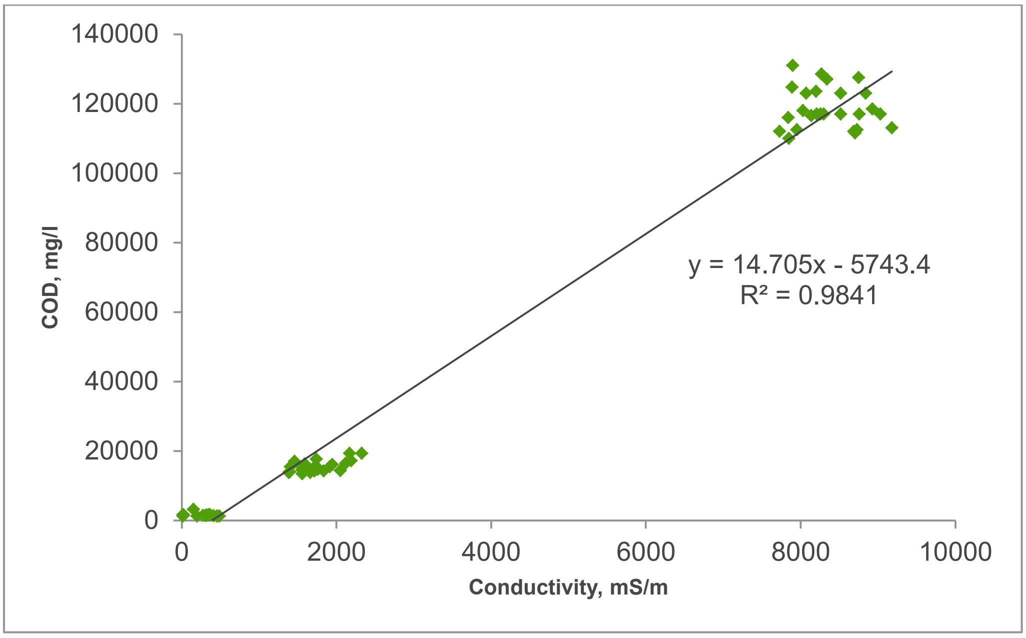


Figure 30. Correlation between conductivity and COD, both analyzed in laboratory.

Figure 31 illustrates the correlation between TDS measured by a refractometer and COD. The correlation coefficient is close to the TDS measured in laboratory. These results suggest a strong correlation of refractometer output and COD and it is in accordance with the results found from the literature.

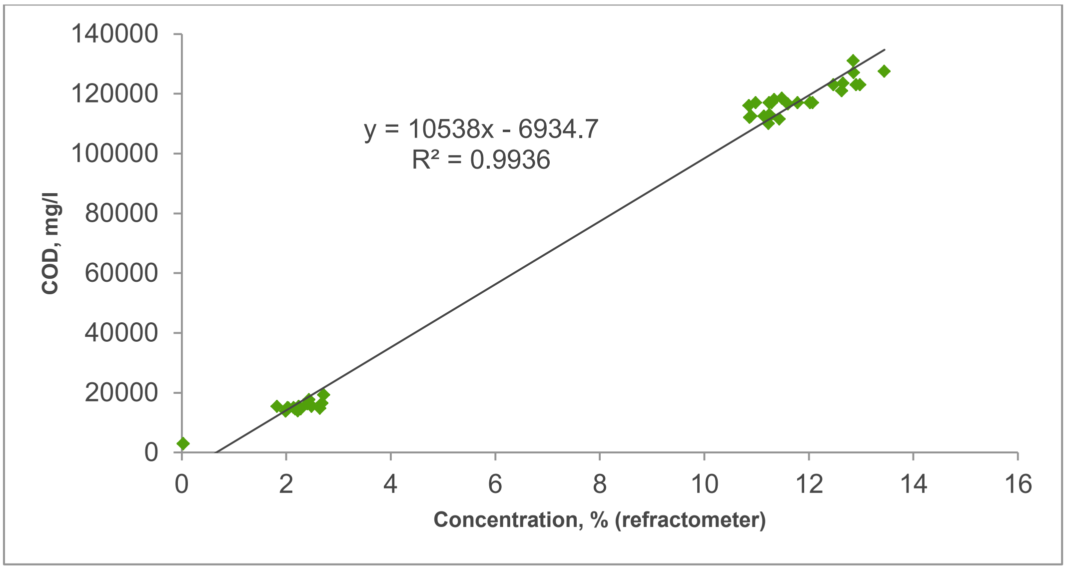


Figure 31. Correlation between TDS measured by refractometer and COD.

Figure 32 illustrates that the correlation coefficient between conductivity and COD is practically zero in narrow concentration scale (3%). This means conductivity is not a proper indicator of COD in liquors when measurement is done in washer specific concentrations scale.

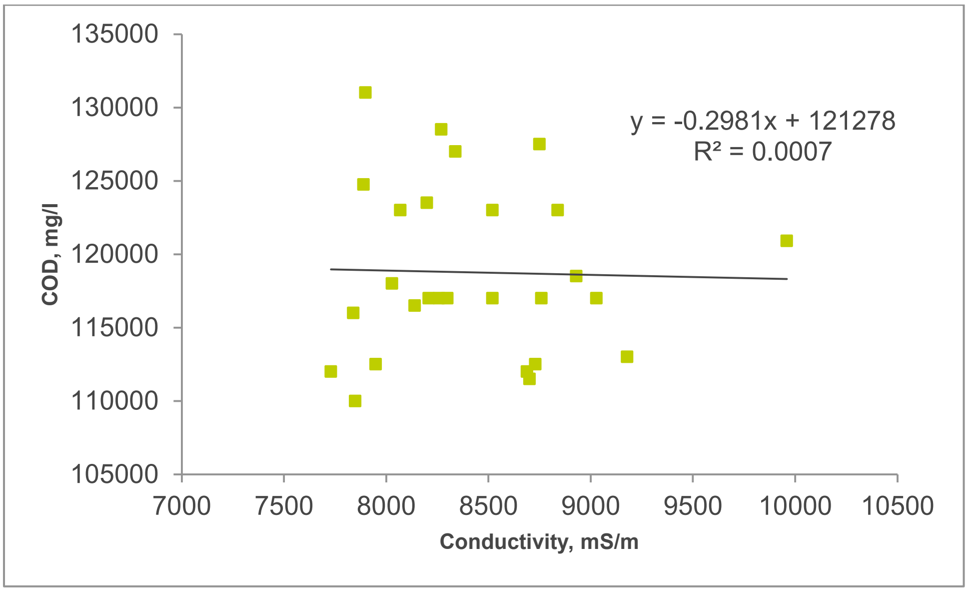


Figure 32. Correlation between conductivity and COD with stronger black liquor. The concentrations of the samples are in between 11.8% and 13.6%.

In figure 33 the correlations between TDS and COD in stronger liquors are represented. Correlation is clear but not perfect as black liquor composition may change rapidly. The concentration range of the samples is about 2%.

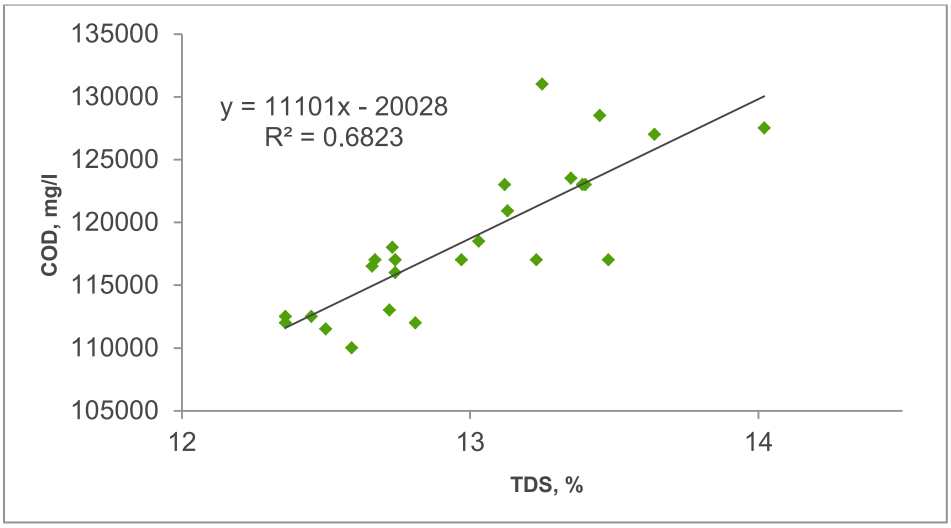


Figure 33. Correlation between TDS analyzed by standard method and COD.

Figure 34 represents the correlation of TDS measured by a refractometer and COD in the same concentration scale used in figure 30. The results indicate that the refractometer measurement gives a rather strong correlation with narrow, washer specific concentration differences in samples. The concentration range of the samples is about 3%.

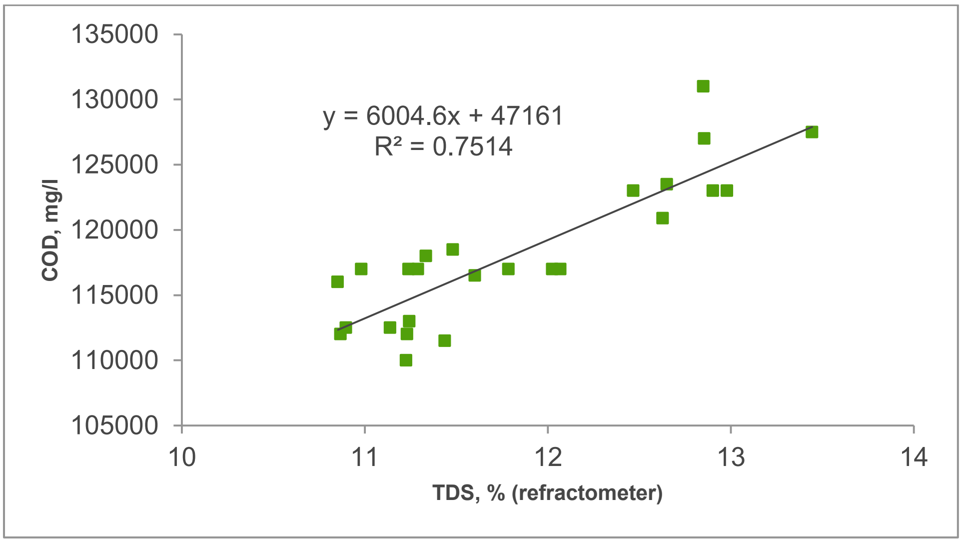


Figure 34. Correlation between TDS measured by refractometer and COD.

9.3 Performance of the installed equipment

The results illustrated in table 6 suggest that the introduction of the upper level control system and refractometers had a significant effect on the performance of the washing line. Wash loss measured in total COD dropped up to 10 percent at the same time as the concentration of the washing liquor leaving the washing line increased 0.4 percent. The production rate was the same in both periods and other important variables were kept constant as well. The table has two comparable periods of two weeks. The comparison was later on made with several months' time frames and proved to give a consistent result. However, the results from longer periods are not presented here due to non-controlled circumstances.

Table 6. Comparison of wash water usage and wash loss between conventional and upper level controls

Control system	Conventional	Upper level
Production	ref	same
Dilution factor m^3/BDt	ref	-0.1
TDS from liquor leaving the washing line, %	ref	+ 0,4
Wash loss to bleaching, kgCOD/BDt	ref	-10%

Figure 35 illustrates the effect the upper level control has had on different wash loss measurements. Wash loss measured by conductivity has experienced the most significant decrease, while TDS decreased slightly less. This result is consistent with the theory examined as the conductivity measurement emphasizes the inorganic portion of total dissolved solids that is easier to wash off than organic compounds such as lignin.

COD measured as kgCOD/BDt expresses all organic material in the pulp solution, including non-dissolved portion such as lignin still adhered to the fiber. The non-dissolved portion cannot be washed away in brown stock washing, leaving the decrease of kgCOD/BDt wash loss more moderate compared to conductivity and TDS. The liquor COD was not measured from the baseline period and thus could not be taken into comparison. However, it is supposed that the decrease in wash loss measured as liquor COD would fall between TDS and kgCOD/BDt.

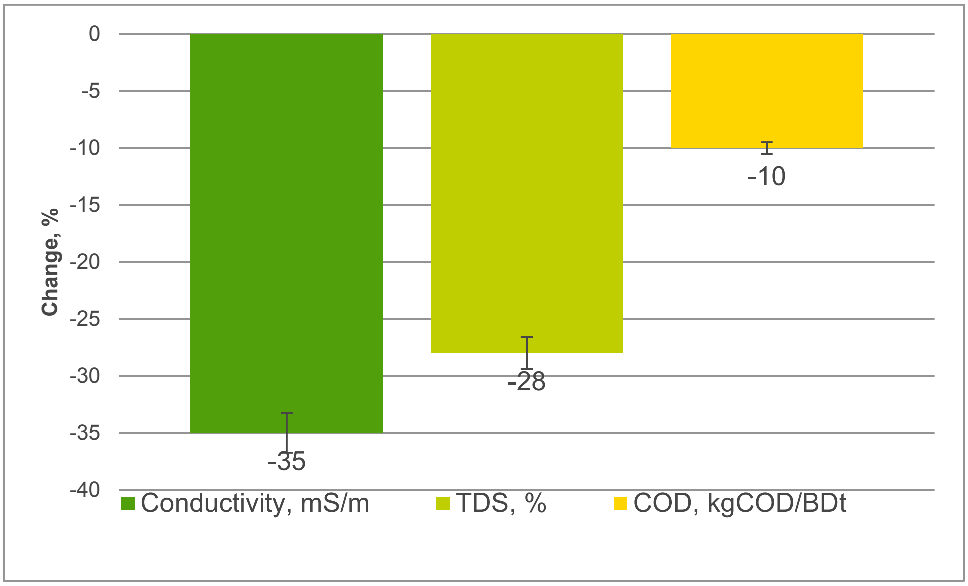


Figure 35. The effect of utilizing upper level control system on different wash loss measurements. Laboratory measurements are from DD3 cake discharge.

Figure 36 represents the kgCOD/BDt wash loss from the baseline period where the washing line was controlled in conventional way and the trial period where the line was controlled by the upper level control system. Both periods were gathered during two weeks and the analyses were made in laboratory. In comparison, the standard deviation of results was smaller when the line was operated using upper level control. In figures 32 – 35 each point refers to a value of one sample taken from the cake discharge of DD3.

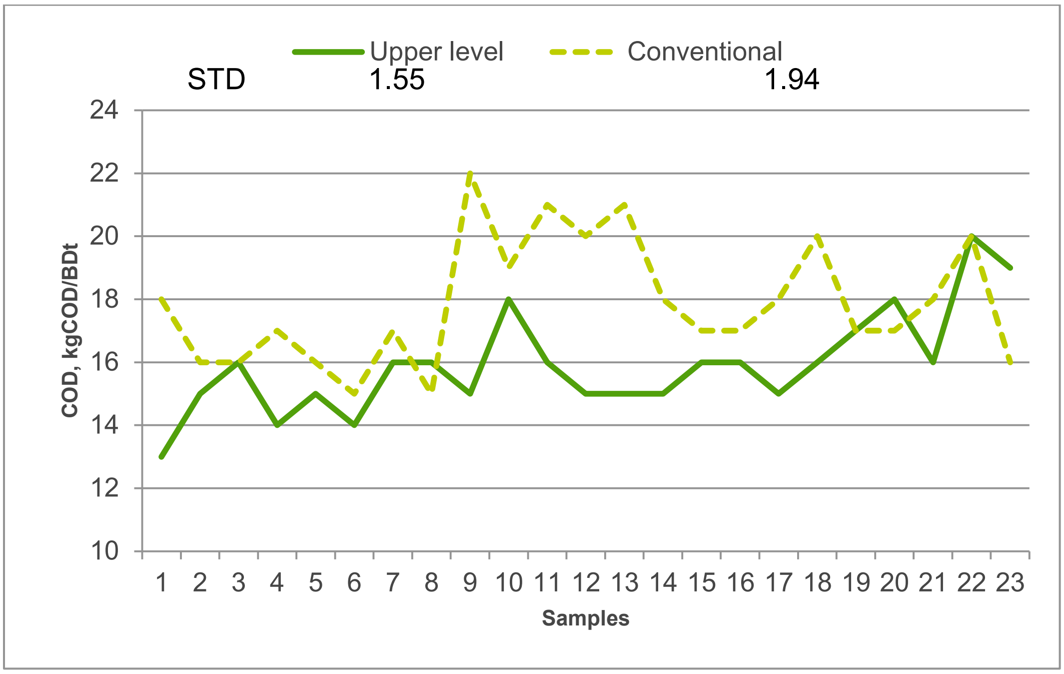


Figure 36. Wash loss measured as kgCOD/BDt during conventional and upper level control. Laboratory measurements from DD3 cake discharge during 2 week period.

Figure 37 illustrates how discharge consistencies changed between two week periods of conventional control and upper level control. It can be seen from the curve and lower standard deviation that discharge consistency has maintained steadier during the upper level control period. The results suggest that dilution factor and drum rotation speed were adjusted in a successful manner.

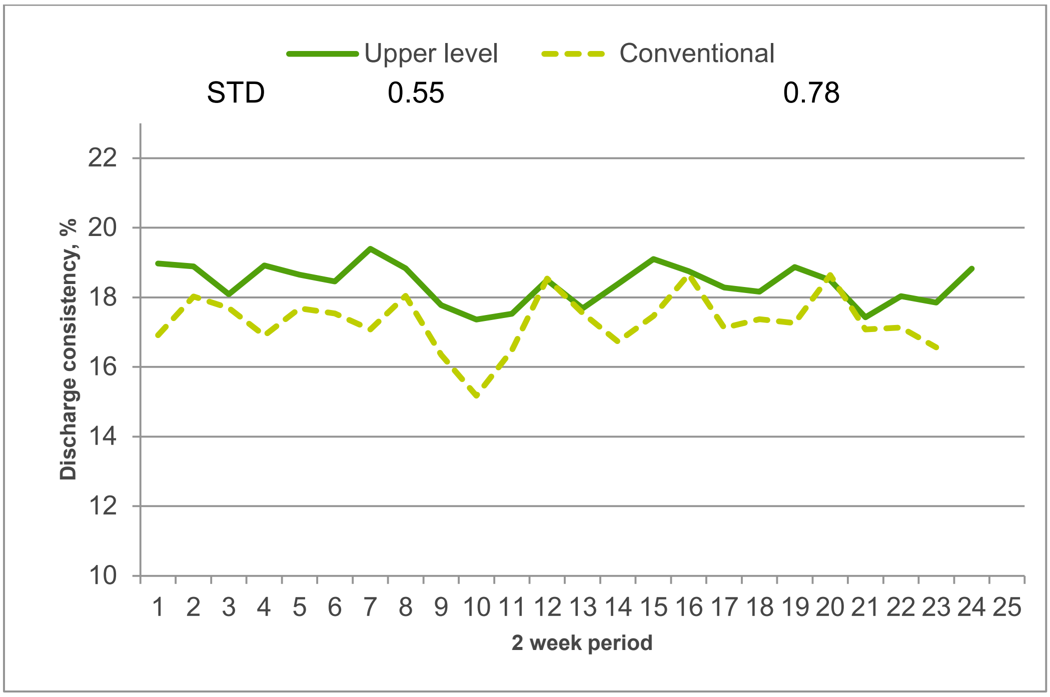


Figure 37 Discharge consistencies during conventional and upper level control periods. Laboratory measurements from DD3 cake discharge during 2 week period.

Figure 38 illustrates how conductivity results have changed during upper level control and conventional control of the line. The results indicate a steadier operation and thus steadier wash loss. Figure 39 suggest same results when wash loss is measured in TDS.

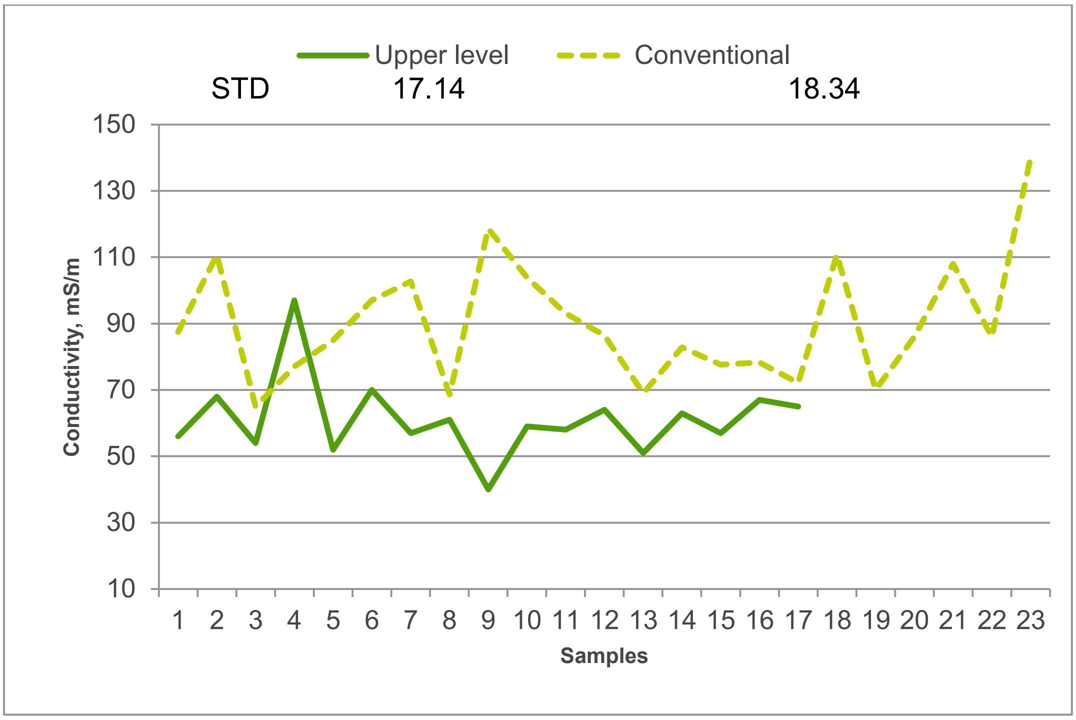


Figure 38. Conductivity during conventional and upper level control periods. Laboratory measurements from DD3 cake discharge during 2 week period.

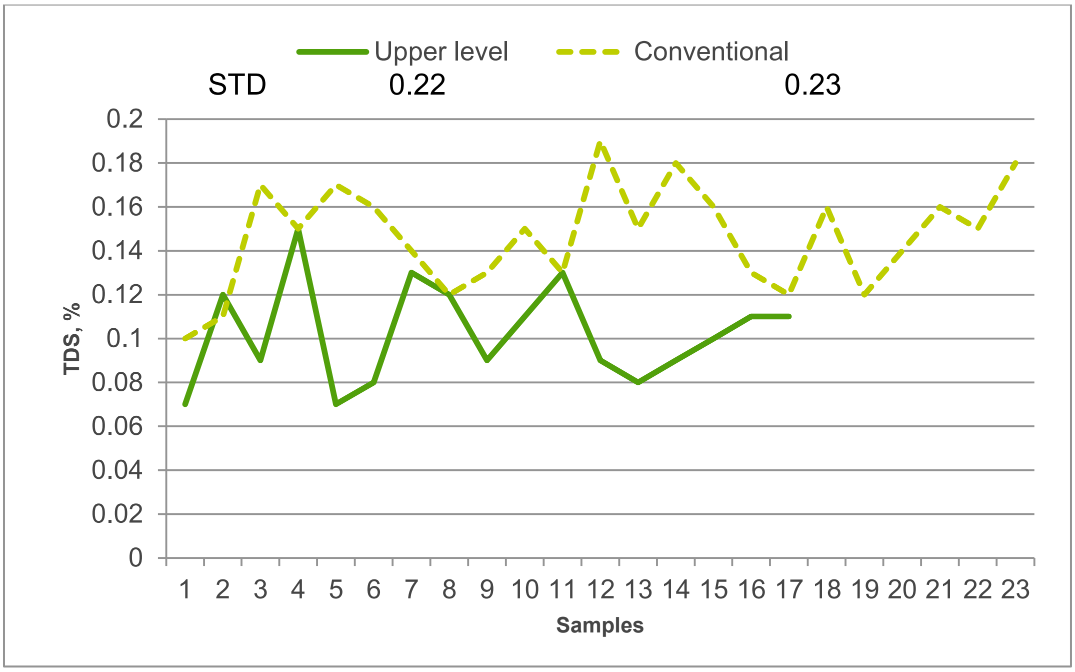


Figure 39. Total dissolved solids during conventional and upper level control periods. Laboratory measurements from DD3 cake discharge during 2 week period.

Steadier control is supposed to be a result of automatic control loops of upper level control as well as unified manner of operation provided by the upper level system. Differences between the “operation philosophies” of different turns undeniably decrease the variation of wash loss. The real time measuring devices enabled immediate response to process changes, which in turn helps to reduce the fluctuation of wash result. The results suggest that the steadier control contributes to smaller total wash loss. Another factor affecting the smaller wash loss is believed to be the torque based control of drum speed, enables the use of higher torque and higher feed pressure.

9.4 Dilution factor control

Figure 40 depicts the measured dilution factor during 48 hours period. In the figure dilution factor control is in use until the red vertical line. After the black dotted line the washer is operated in a conventional way by manually adjusting the amount of washing liquid. During both periods the production rate varied between 31 ADt/h and 41 ADt/h. Period between the two lines experienced process disturbances and cannot be considered reliable.

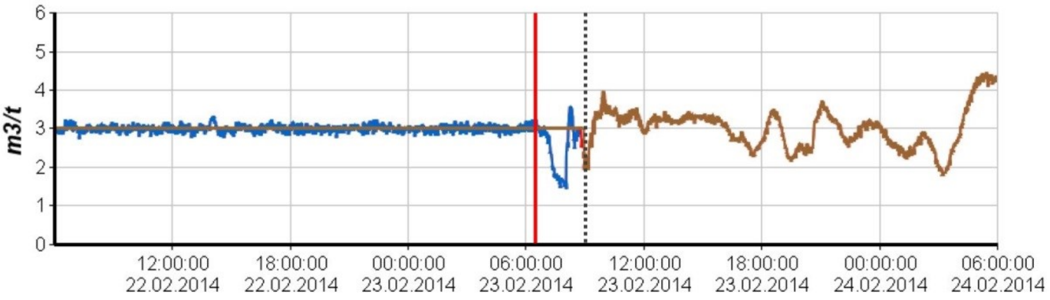


Figure 40. Effect of dilution factor control on measured dilution factor

Figure 41 from DD3 represents the effect upper level dilution factor control had on measured wash loss. Solid trend line represents dilution factor based on measured flows and dotted line expresses the wash loss as conductivity measured on line. Between the red vertical lines the washer was operated with conventional control system and on both sides of the line the dilution factor control was in operation. The yellow slashed areas had unusual process disturbances. It can be seen from the chart that the measured dilution factor varied significantly when dilution factor control was turned off. Consequently, the wash loss varied more than with dilution factor control.

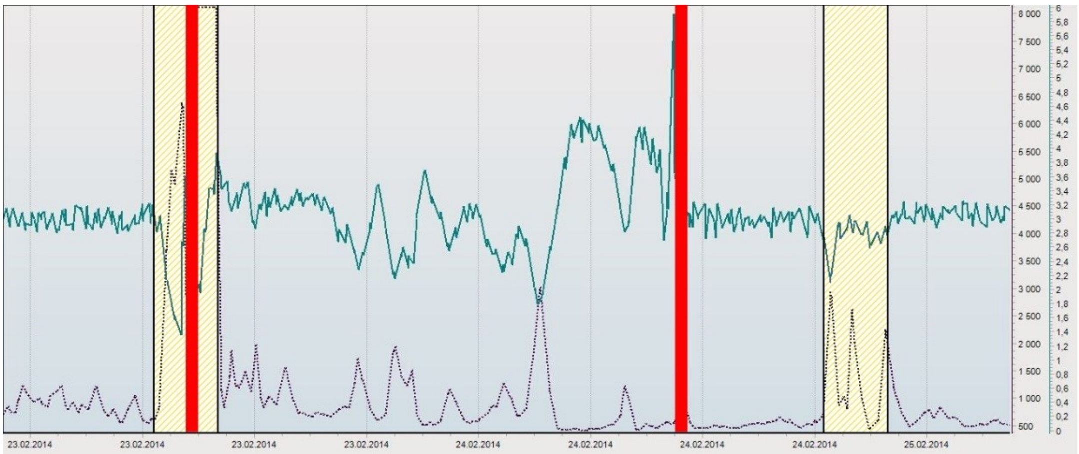


Figure 41. Effect of DF control on measured wash loss measured by conductivity meter.

The columns on figure 42 represent the average TDS wash loss from trial periods with different dilution factors measured both as standard method and refractometer. The level of wash loss measured by refractometer appears higher than the standard method. This is because the laboratory results were taken from the cake discharge of DD3 while the refractometer was placed at a liquor line leaving the vacuum container of DD3. At the location of the refractometer the wash loss is slightly higher compared to the cake discharge. The results suggest that by increasing dilution factor from 3.5 to 4.5 it is possible to achieve up to 55 percent decrease in TDS wash loss.

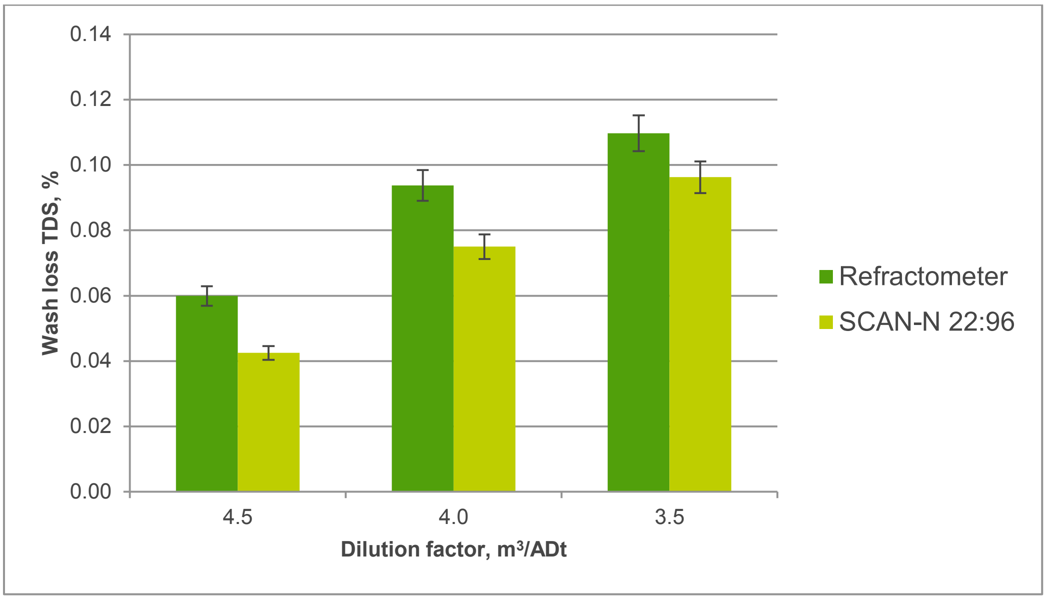


Figure 42. Wash loss as a function of dilution factor. TDS measured by refractometer and TDS analyzed in laboratory.

Figures 43 and 44 represents the effect of dilution factor on kgNa_2SO_4/BDt, kgCOD/BDt and gCOD/l wash loss. The results are presented as average wash loss from each trial period. The wash loss measured as kgNa_2SO_4/BDt suggest a decrease of 18 percent when dilution factor was dropped from 4.5 to 3.5. The decrease in liquor COD was 13 percent with the same period of trial.

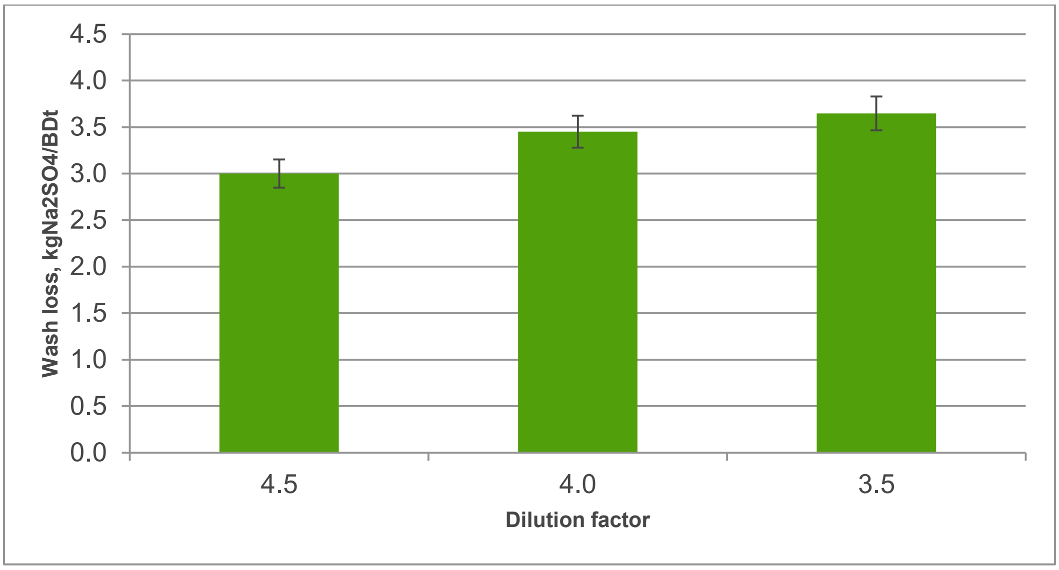


Figure 43. The effect of dilution factor on kgNa_2SO_4/BDt wash loss. Laboratory analysis.

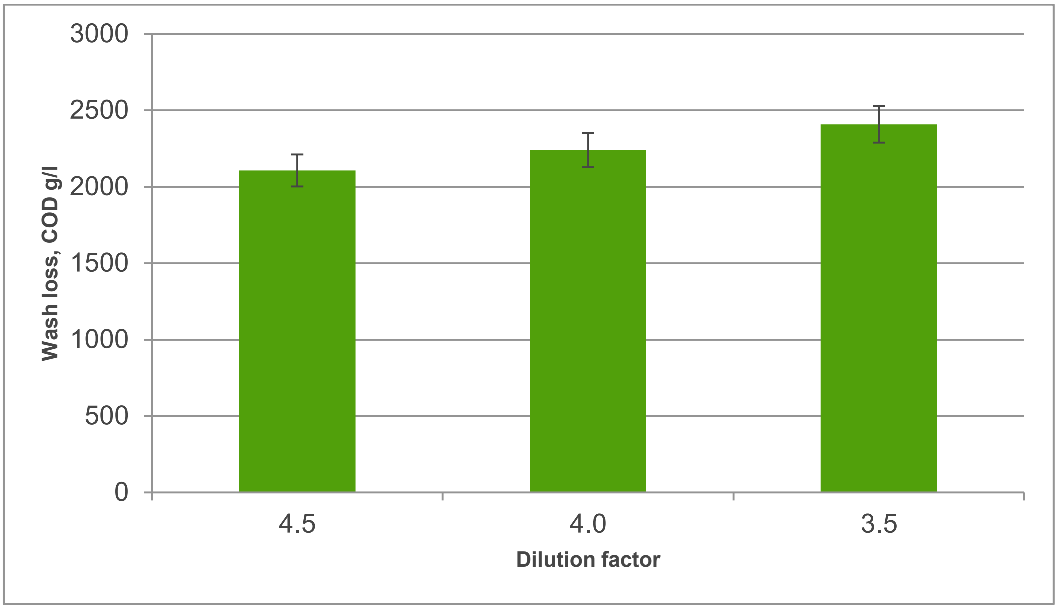


Figure 44. The effect of dilution factor on gCOD/l wash loss

In case of wash loss measured in kgCOD/BDt represented in figure 45, the wash loss achieved by higher level dilution factor is higher than that of the normal level. This is believed to be because during the trial period of the 4.5 dilution factor the kappa number was higher than that of the 3.5 and 4 dilution factor periods. For the period of 4.5 the kappa number was 11.5, while during the two other periods it was 10.7 and 10.9. The higher kappa number suggests higher lignin content i.e. higher COD adhered to the fiber, which could not be washed off.

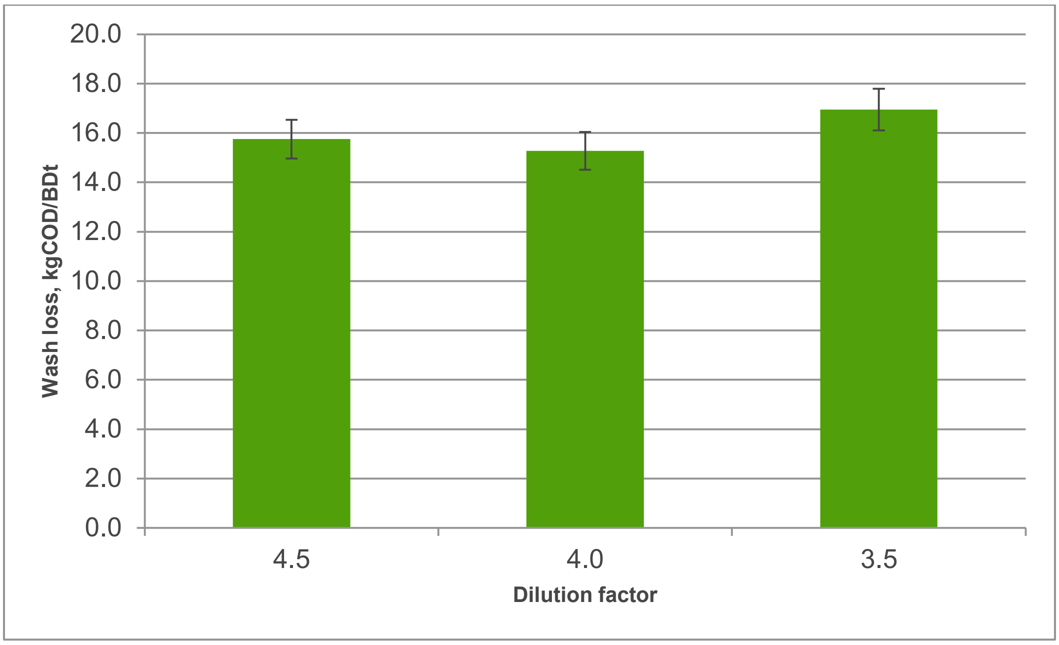


Figure 45. The effect of dilution factor on kgCOD/BDt wash loss on DD1&DD2

Figure 46 represents the combined effect of dilution factor on wash loss from DD1 and DD2 washers. The wash loss was obtained by refractometer measurement (4) and is presented as the amount of dissolved solids per ton of bone dry pulp. The ratio of kgCOD/BDt to kgDS/BDt in this stage of the washing is approximately 1.4, which means 100kgDS/BDt equals 140kgCOD/BDt. From the result it can be stated that an increase in the dilution factor clearly decreases the wash loss. During the trial a test was performed to decrease the dilution factor to a lower level until meeting the limit where the wash results collapses. This was done, but it proofed rather difficult to get data from these attempts because the circulation of the wash liquor between the washing zones would stop, deteriorating rapidly the wash result of the whole washer. This happened when dilution factor was fewer than 2.7 for DD2 and 2.8 for DD1.

The above mentioned DD washers are originally designed to operate on lower production levels. Nevertheless, the washers proved to have capacity for the production rate they are running on and even higher. The disadvantage they had was the wash liquor circulation system which tended to be error-prone and stop the circulation with high production rate, low dilution factor or high consistency.

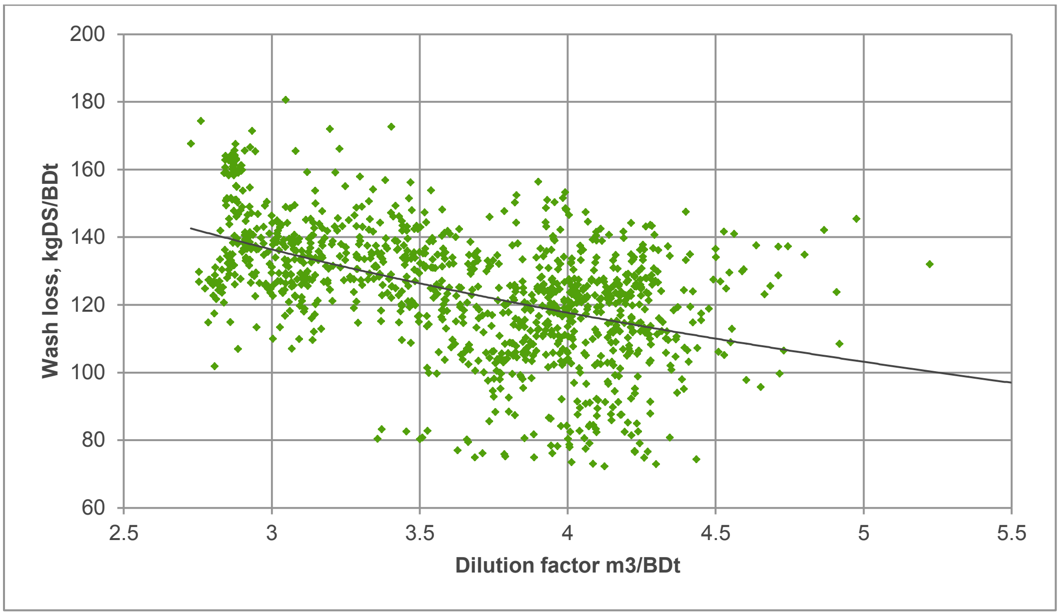


Figure 46. Effect of dilution factor on kgDS/BDt wash loss from DD1 and DD2.

Figure 47 illustrates the effect of dilution factor on DD3 wash loss measured by refractometer and expressed as kgDS/BDt. During the trial the production rate was maintained constant. It can be seen that a higher dilution factor produces lower wash loss. Moreover, the effect of dilution factor to wash loss is significantly higher than in case of DD1 and DD2. The dilution factor level is lower than that of the whole washing line due to washer bypass.

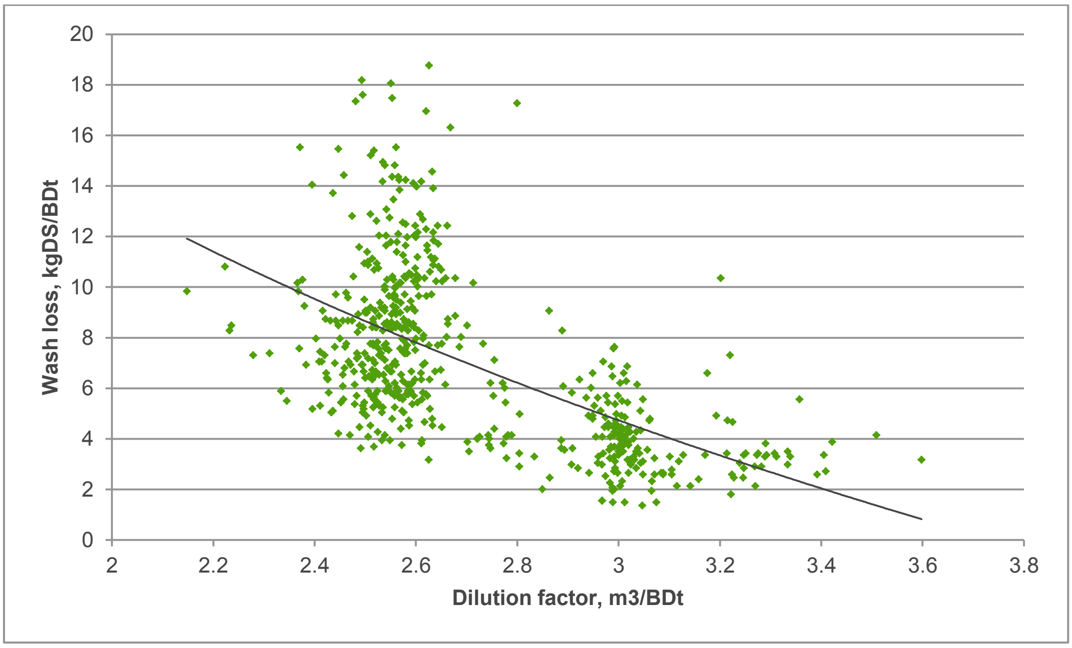


Figure 47. The effect of dilution factor on kgDS/BDt wash loss from DD3.

9.5 Production rate

Figure 48 represents the effect of production rate on wash loss measured by refractometer and expressed as kgDS/BDt. The result is measured from DD3. Dilution factor of the washing line was 3.5m^3/BDt during the entire trial. Results suggest that higher production rate increases washing loss, especially when the production rate is taken higher than in normal operation.

During the trial the washing line experienced many disturbances. When the production rate was taken over 1000 ADt/d the DD1 and DD2 wash liquor circulation system stopped circulating various times. As a consequence the wash loss increased rapidly and the production rate had to be decreased and increased again after the wash liquor circulation recovered. One significant reason for the rapid deterioration of the wash result was thought to be the insufficient capacity of the pulp feed pump. The pump could not maintain steady feed rate of the pulp when the production rate or feed consistency was increased.

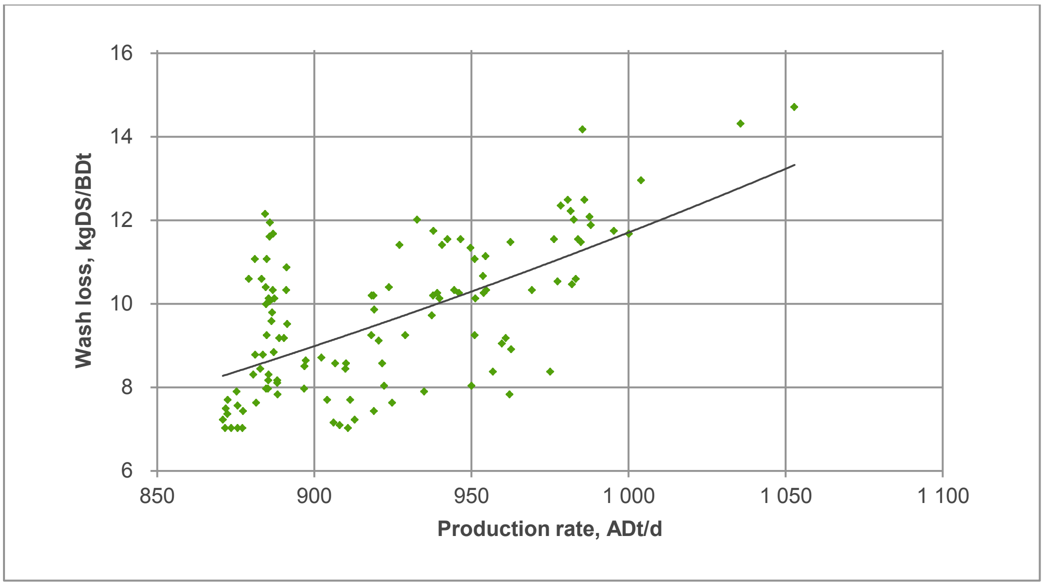


Figure 48. Effect of production rate as ADt/d to wash loss in kgDS/BDt measured by refractometer.

9.6 Feed consistency

In figure 49 is represented the wash loss from DD1 and DD2 as a function of feed consistency. The results indicate that by using lower feed consistency a lower wash loss could be achieved. However, during the trial many process disturbances occurred deteriorating the reliability of the result. For example, the pulp feed pump could not maintain a steady feed rate to the washers if the consistency was increased to a higher level. This caused disturbances and increased the wash loss when the consistency was higher. The trial should be repeated with more potent pulp feed pump to assure the correctness of the result.

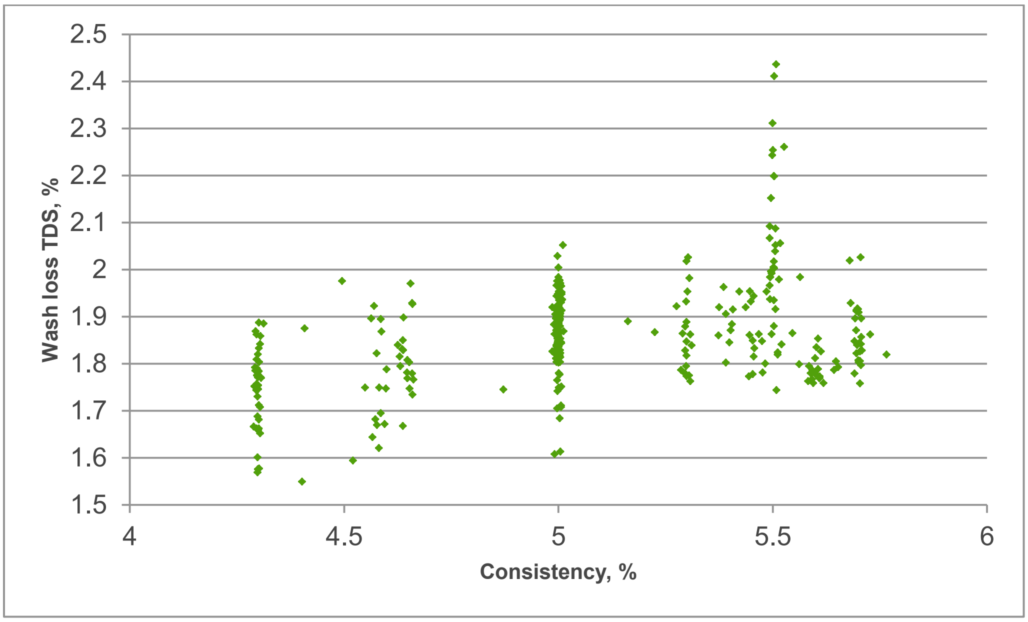


Figure 49. Wash loss as a function of washer feed consistency.

9.7 Drum torque

The drum torque control seemed to have a positive effect on the performance of the washer. Figure 50 illustrates that the higher the torque, the smaller and more stable is the wash loss. When the torque was taken under 160 kNm the washing result collapsed resulting in significant increase in wash loss. Experiences during trials suggested that the level where washing result collapses depends on the stock properties and could vary greatly.

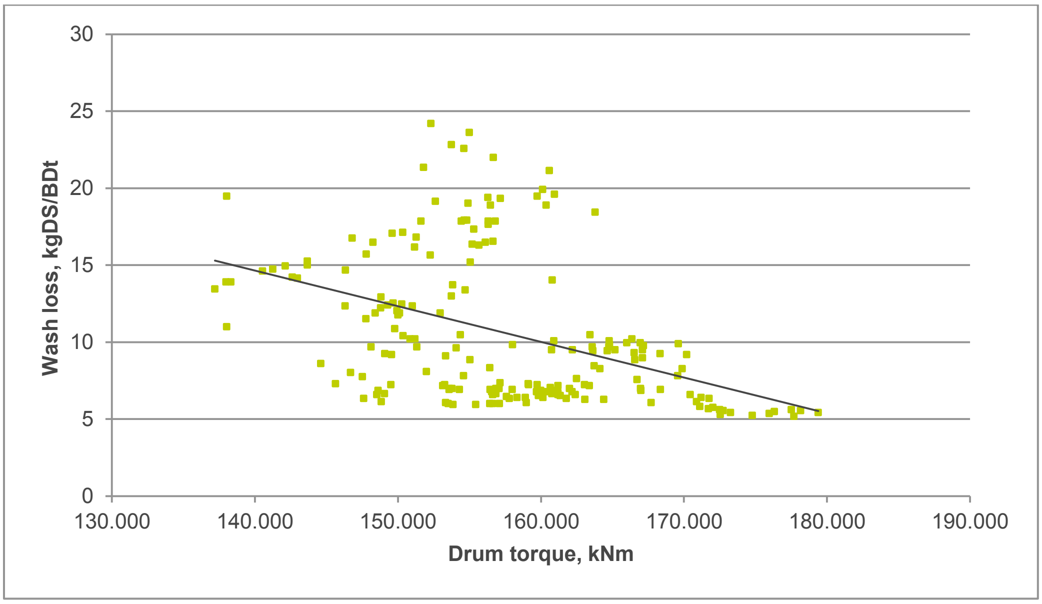


Figure 50. The effect of drum torque to wash loss. Wash loss is measured by refractometer and expressed as kgDS/BDt.

9.8 Payback time

The payback time for the investment on upper level control system and 8 refractometers was calculated according to the results obtained during the performance trial. The calculation was done by using equation 12. The increased cash flow was calculated by summing savings from evaporation plant as less steam used and from bleaching plant as less chemicals consumed. The calculated payback time fulfilled the objective easily.

Figure 51 represents the portion of saving resulting from less evaporation and less chemical consumption. It can be seen that at the specific plant savings from evaporation plant were almost double in comparison to saving from bleaching plant.

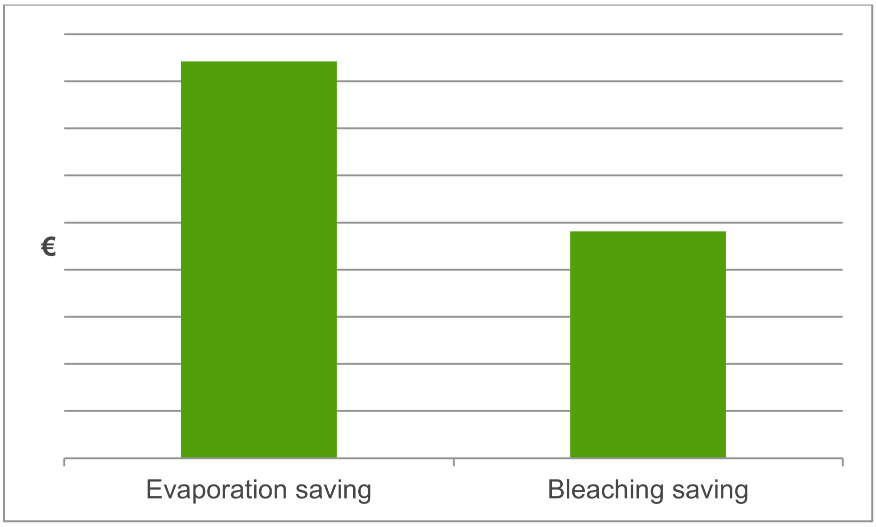


Figure 51. Savings deriving from evaporation and bleaching department.

10 Summary of experimental work

The results suggest that by using an upper level control system to control the dilution factor of the entire brown stock washing line, by real time wash loss measurements as control feedback and by torque control of DD-washers rotation speed it is possible to reduce the amount of brown stock wash loss and simultaneously decrease the amount of used wash water. In this work the upper level control system together with the refractometers were taken into service and the performance was tested.

Analyses proved that a measurement performed by refractometer expresses the total dissolved solids of the liquor, while conductivity meters emphasize the inorganic matter and are more vulnerable to other process changes such as pH and temperature.

The created “floating torque set point” for the drum torque automatically provides the DD washer an optimum torque set point for the changing pulp properties. The floating set point enables a more stable washing result and the use of higher level feed pressure in the washer.

High drum torque proved to give lower and more stable wash loss. The washing efficiency collapses when the drum torque falls under certain level. The level where the washing result collapses varies greatly.

Higher production rate deteriorates the washing efficiency and makes the washing line more vulnerable to disturbances. This is especially the case with DD1 and DD2.

The dilution factor of the washing line has a great effect on the washing result. However, the amount of wash loss varies significantly when evaluated by different methods to measure wash loss.

11 Conclusions and proposals for improvements

11.1 Upper level control system

The created upper level control system proved to enhance washing efficiency of the washing line. The increased washing efficiency was a result of several factors including dilution factor control of the whole washing line, drum torque control, unification of operational philosophies and derived from all these components, the steadiness of the line- and washing result.

The control of the liquor balance enabled effective utilization of all wash water fed to the washing line. In the conventional control the DD3 was bypassed continuously, while in the upper level control the bypassing valve could be closed entirely. Instead of using the DD3 bypassing valve, all the wash water used in the line was fed through DD3, thus increasing the dilution factor of the washer without introducing extra water to the washing line.

The on-line dissolved solids and conductivity feedback for the dilution factor control maintained the wash loss on a desired level by adjusting the dilution factor according to process conditions. According to the analyses made it was useful to use both on-line measurement devices as feedback for the dilution factor control, as the methods emphasize different substances in the liquor.

Another element was the control of the drum rotation speed based on drum torque. The torque control proved to maintain the washing consistency higher and steadier than the conventional feed pressure control, delivering a higher washing efficiency. The created “floating torque control” automatically set the optimum torque level for the washer depending on pulp properties. This was seen as a useful tool, as the pulp properties tended to change significantly.

From the operational point of view the upper level control is more automated compared to the conventional control, meaning less active operation time and more ease in surveillance. However, in case of disturbances the operators must be able to make changes to the parameters and do the required trouble-shooting. In order to achieve the adequate knowledge level, a well-established operator training is essential for effective operation of the line. Moreover, it would be useful to train few key users, who could control the fine tuning parameters and address more complex problems. In addition, more effort should be made to simplify the upper level control so that it would be easier for the operators to adopt.

For future study, it would be interesting to construct the upper level control system with wash result feedback for the dilution factor control from pre O_2 washers. In this case post O_2 washer wash water feed would follow the wash liquor balance of pre O_2 wash liquor tank surface level. This would supposedly lead to a more instant response on changes in wash loss starting from the beginning of the line and, respectively, the control would maintain steady the wash loss leaving from first wash phase. The faster response in the beginning of the line would also provide better control of the line in cases of process disturbances.

Another advantage of this system would be the full utilization of the refractometer in the pulp line entering the washing line. Using wash liquor feedforward according to the concentration of the liquor from cooking could help to keep the liquor concentration of the whole line in a desired level. Moreover, the concentration of the liquor from cooking tends to vary greatly in relatively short time periods, especially in batch cooking processes. This somewhat rapid variation in the concentration could be balanced already in the beginning of the line.

11.2 On-line measuring devices

The installation sites of the refractometers proved to provide enough information for comprehensive washing line monitor and control. Washer performance parameters such as the E-value and displacement ratio were calculated successfully and monitored real-time. The parameters gave important information on the washer performance and indicated if washer suffered deterioration in performance.

The deployment of the refractometers went well, excluding the last wash loss measuring site i.e. refractometer number 8. The sulfuric acid added at the site factors disabled the use of the measurement. A calculation was created to compensate the effect of sulfuric acid to the measurement, but the flow was not stable and thus the compensation was not successful. The refractometers installed in liquor line dirtied during time and steam washing devises were installed on them.

In concentration scale of the whole washing line both refractometer and conductivity correlate strongly with COD. However, when making the comparison in washer specific concentrations the results suggest that conductivity measurement is not capable of providing information on the COD level of liquor in a certain washer. On the other hand, refractometer measurement proved to be a useful tool to indicate liquor COD changes even washer specifically. However, in order to obtain the most accurate result the COD/TDS correlation should be created for each refractometer installation site individually. This is due to the fact that liquor composition changes depending on the location.

As a wash loss assessment, the conductivity measurement works as a rough feedback and indicate the direction of the process changes, while refractometer provides the actual amount of wash loss with good precision even in narrow concentration scales. Moreover, refractometer provides the possibility to use performance parameters such as E-value and displacement ratio to continuously monitor and develop washing efficiency. The possibility to install the measurement in pulp line is another advantage of refractometer. The benefits of conductivity are simplicity of the measuring device and small capital investment.

The utilization of both measuring devices would produce the most accurate wash loss measurement and optimum feedback for a dilution factor control due to the tendency of the methods to measure different substances in the liquor.

According to the analyses made the standard oven drying method appears not suitable for dissolved solid analysis from secondary condensate due to some volatile compounds evaporating in the analysis. Therefore, it would be interesting to monitor the secondary condensate dissolved solids on-line using refractometer.

One of the refractometers was installed in a location where antifoaming agent was added. The antifoaming agent did not affect the refractometer measurement. Nevertheless, in further studies it would be interesting to analyze the possible effect antifoaming agent might have on the dirtying of the prism of the refractometer. The refractometer had to be cleaned after some process disturbances because of a small layer of deposit on the surface.

11.3 Brown stock washing line performance

The wash result of the brown stock washing line is generally acceptable at the fiber line 1. The experience and information gathered during the introduction period and the trials suggest that, in comparison to the conventional control, the wash water amount, i.e. dilution factor should be decreased in the washing line in order to achieve the optimum economic and environmental performance. During the trials this was accomplished. However, longer period trials are recommended to assess the effect of dilution factor to bleaching chemical consumption.

The trials proved that the DD1 and DD2 tend to encounter problems in the wash liquor circulation lines, when production rate or feed consistency were increased too high or when dilution factor was lowered under tolerable limit.

One factor causing disturbances for the above mentioned washers is thought to be the feed pump, which did not have the capacity to deliver steady flow to the washers. After the trials the feed pump was updated to a more potent one and it is suggested that the production rate and feed consistency trials be repeated.

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