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WATER CONSUMPTION IN BOARD MACHINE AND POSSIBILITIES FOR OPTIMIZATION

Master's Thesis

Examiners: Prof. Mika Mänttäri

M.Sc. (Tech.) Jenni Latva-Kokko

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
School of Engineering Science
Kemiantekniikka

Aino-Maria Rimpeläinen
Kartonkikoneen vedenkulutuksen kartoitus ja optimointimahdollisuudet

Diplomityö

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Tarkastajat: Prof. Mika Mänttäri
DI Jenni Latva-Kokko

Hakusanat: kartonki, vedenkulutus, kiekkosuodin, superkirkassuodos

Työn tarkoituksena oli selvittää vedenkulutuksen optimointimahdollisuudet kartonkikoneella. Kartonkikoneen vedenkulutus määritettiin, ja kiekkosuotimen superkirkassuodoksen käytössä havaittiin optimointimahdollisuus. Kiekkosuodinta käytetään kartonkikoneen hylkyjärjestelmässä. Kiekkosuotimelta erotetaan kolme vesijaetta, joista superkirkassuodos on puhtain. Superkirkassuodos käytetään tällä hetkellä kartonkitehtaalla kartonkikoneen 0-vesikierrossa. Työn tavoitteena oli selvittää, voisiko superkirkassuodosta hyödyntää kartonkikoneen lämminvesikierrossa korvaamaan tuorevettä.

Työn kirjallisuusosassa kartonginvalmistusprosessi kuvataan lyhyesti ja vedenkäyttö kartongin valmistusprosessissa esitellään. 0-veden laatu, 0-veden analyysimenetelmät ja laatuvaatimukset esitellään. Kirjallisuusosan lopussa käsitellään kartonkitehtaan sisäisiä vedenpuhdistusmenetelmiä ja tutustutaan kartonkikoneeseen, jota käsitellään työn kokeellisessa osassa. Kokeellisessa osassa suoritettiin vedenkulutuksen kartoitus. Superkirkassuodoksen laatu analysoitiin ja vedenkäytön optimoinnin vaikutuksia arvioitiin mittauksiin perustuen. Superkirkassuodosta suodatettiin membraanitekniikalla ja suodatuskankaalla, jotta voidaan määrittää tarvittava käsittely tavoitepuhtauteen yltämiseksi.

Tulosten perustella kartonkikoneen vedenkulutusta voisi vähentää 30 %, jos 50 % kiekkosuotimella syntyvästä superkirkassuodoksesta ohjattaisiin lämminvesikiertoon. Tuloksien perusteella olisi suositeltavaa käsitellä suodosta ennen lämminvesikiertoon johtamista kiintoaineen poistamiseksi ja kemiallisen hapenkulutuksen sekä johtokyvyn pienentämiseksi. Suodatuskokeista vain RO membraanilla saavutettiin tuoreveden puhtaus, vaikka myös NF ja UF membraaneilla yllettiin korkeisiin retentioihin. Myös perinteisen suodatuksen menetelmiä, kuten hiekka- ja painesuodatusta, voisi hyödyntää suodoksen puhdistukseen, jolloin vedenpuhdistuksen kulut olisivat alhaisemmat. Näillä menetelmillä suodoksesta saadaan poistettua kiintoainetta.

ABSTRACT

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Water consumption in board machine and possibilities for optimization
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86 pages (+1), 26 figures, 12 tables (+2) and 1 appendix

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Keywords: paperboard, water consumption, disc filter, super-clear filtrate

The aim of this thesis was to determine the water consumption optimization opportunities in a board machine. Water consumption was determined, and an optimization possibility was discovered in disc filter's super-clear filtrate. Disc filter is used in the broke system, and three water fractions are obtained from it of which the super-clear filtrate is the purest. Currently, super-clear filtrate is used in board machine white water loop. The purpose of the thesis is to determine if super-clear filtrate could be applied in the board machine heat recovery loop to replace fresh water.

In the literature review of the thesis, board production process is briefly addressed and water use in the production is reviewed. The composition of white water, that contains the super-clear filtrate, is then described followed by the analysis methods and quality requirements for reusable water. Last, internal water treatment technologies to purify the board machine waters are reviewed and the board machine in question is introduced. In the experimental part, the water consumption survey is addressed. The quality of super-clear filtrate is analyzed, and the effect of water use optimization is estimated based on the analysis. Membrane technology and filtration with filter cloth is applied to treat the filtrate to determine the required treatment to achieve the target purity of filtrate.

It was concluded that by applying 50 % of the produced super-clear filtrate to the heat recovery loop, water consumption could be reduced by 30%. Based on the results, it was recommended to treat the filtrate before utilizing in the heat recovery loop to remove solids and decrease COD and conductivity. From the filtration experiments it was concluded that only with RO membrane the quality of fresh water was achieved although high retentions were achieved also with NF and UF membranes. Also, conventional filtration technologies, such as sand or pressure filtration, could be applied in treatment of super-clear filtrate to reduce the costs of treatment. With these technologies solids can be removed from the filtrate.

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Aino Rimpeläinen
Lappeenranta, 31st of May 2021

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

BM1	Board Machine 1
BOD	Biochemical oxygen demand
CFU	Colony forming unit
COD	Chemical oxygen demand
CTMP	Chemi-thermomechanical pulp
DAF	Dissolved air flotation
DCS	Dissolved and colloidal substances
MF	Microfiltration
MWCO	Molecular weight cut-off
NF	Nanofiltration
PWP	Pure water permeability
PWP_a	Pure water permeability after filtration
PWP_b	Pure water permeability before filtration
RO	Reverse osmosis
SCF	Super-clear filtrate
SS	Suspended solids
SWC	Specific water consumption
TDS	Total dissolved solids
TOC	Total organic carbon
TSS	Total suspended solids
UF	Ultrafiltration

SYMBOLS

A	Filtration area	$[\mathrm{m}^2]$
C^{Feed}	Concentration of observed parameter in the feed	
C^{Permeate}	Concentration of observed parameter in the permeate	
J	Mass flux	$[\frac{\mathrm{kg}}{\mathrm{m}^2\mathrm{h}}]$
k	Percentage of SCF from disc filter feed	[%]
m_1	Mass of filter paper	[mg]
m_2	Mass of filter paper and sample	[mg]
m_{p}	Mass of permeate	[kg]
P	Permeability	$[\frac{\mathrm{kg}}{\mathrm{m}^2\mathrm{hbar}}]$
p	Pressure applied in filtration	[bar]
Q	Specific water consumption	$[\frac{\mathrm{m}^3}{\mathrm{t}_{\mathrm{board}}}]$
Q_{SFC}	Generation of SCF per ton of board	$[\frac{\mathrm{m}^3}{\mathrm{t}_{\mathrm{board}}}]$
R	Production of BM1	$[\frac{\mathrm{t}}{\mathrm{h}}]$
t	Time	[h]
V_1	Volume of sample	[ml]
$\dot{F}$	Volumetric flow of broke to disc filter	$[\frac{\mathrm{m}^3}{\mathrm{h}}]$
$\dot{V}$	Volumetric flow of wastewater	$[\frac{\mathrm{m}^3}{\mathrm{h}}]$

1 INTRODUCTION

Pulp and paper industry is one of the most water-consumptive industries. In Europe pulp and paper industry is the second highest fresh water consumer, and it generates annually 6 trillion liters of wastewater (Lacorte et al. 2003). In order to achieve the demands set by stricter legislation, pulp and paper industry has developed its processes into a more sustainable direction. Tenno and Paulapuro (1990) proposes the most significant development regarding the water consumption in papermaking being the closure of water cycle which has enabled a substantial reduction of fresh water consumption. In multiply board production the specific fresh water consumption has decreased around 88 % to 94 % compared to a situation nearly 40 years ago according to Weise et al. (2008).

Closing the water cycle means that less fresh water is consumed in the processes and less effluent exits the processes. Water is reused in the production process, and in integrated mills exiting water can be consumed at another process stage. However, the problem with water reuse is the enrichment of disturbing substances in the circulating water which causes process runnability and quality problems (Tenno & Paulapuro, 1999). With higher degree of closure of water cycle the threat of accumulation of disturbing substances into the process waters is more severe. In order to prevent disturbing substances accumulation in the water circuits, on-site water treatment is required (Nuortila-Jokinen et al. 2004). On-site water treatment has enabled water reuse, ensured stable production and decreased the generation of wastewater (Choi et al., 2003). By gaining purer process water less fresh water is required in the high-purity applications such as board machine’s shower waters. In addition, by identifying the effluent flows from the mill, new, recyclable flows can be recognized, and effluent formation decreased.

1.1 Objectives and scope

This master’s thesis focuses on identifying the water consumption at a board machine and presents on-site water treatment technologies for water purification. The aim is to investigate the optimization opportunities of water use in board production and evaluate the impact the water use optimization has on the production process. This thesis attempts to increase the sustainability of board production by providing solutions for reducing fresh water consumption.

The main objectives of this study can be aggregated to three research questions that address the water use in board production, the quality of water used in the processes and the means to optimize the water use. The research questions are presented in Figure 1 with the objectives of each question. The similarity of water management in board and paper production is obvious due to similar production processes. Due to this similarity water use both in paper and in board production is addressed to gain a comprehensive understanding of the water use. However, to be precise there are differences in water use with different paper and board grades which are not addressed in this thesis.

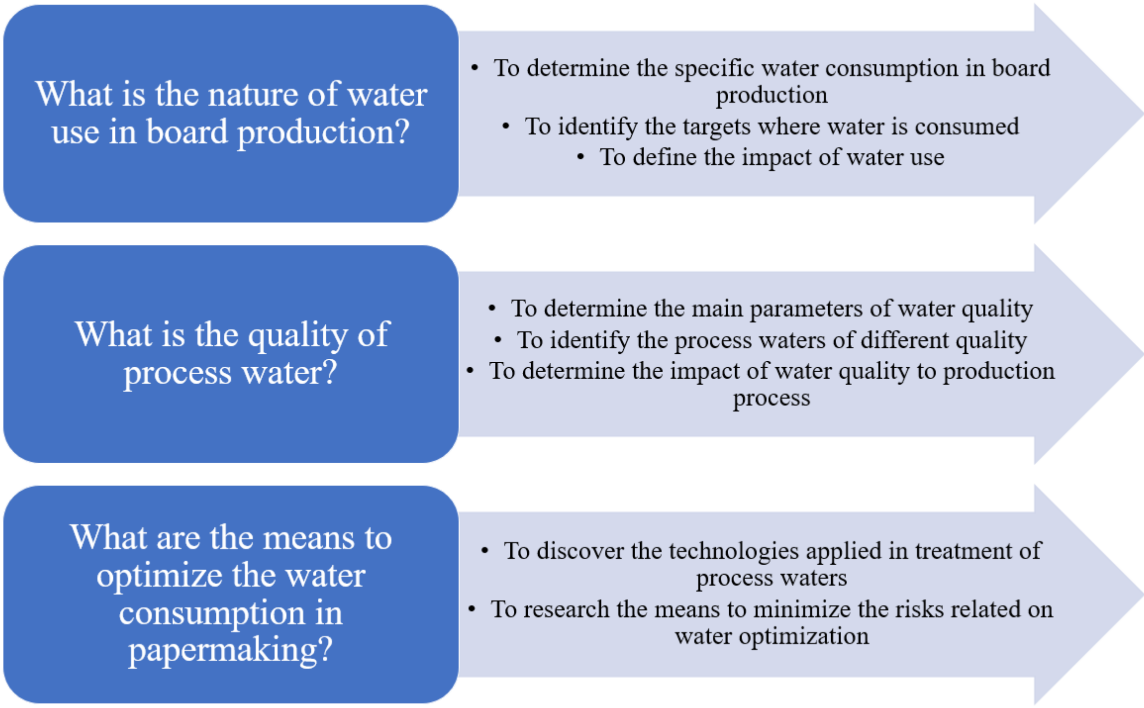

Figure 1 The research questions of the thesis and their objectives.

Although pulp production is a significant process step of the board production from raw materials to the finished product, it is not considered in the water consumption survey. The scope is limited only to the board machine. So, the water use related to stock preparation in the board mill, board production and the effluent discharged from board mill are included in this study.

1.2 Execution of the study

The research process is based on the set research questions. First, literature from related area is explored after which the existing knowledge is applied in the case of Board Machine 1. By finding the answers to the research questions the goal of this thesis can be accomplished.

This study was carried out from December 2020 until May 2021. The literature review is executed from December 2020 until January 2021. In the end of January the experimental study plan is created, and the experiments are started in February. The last experiments are finished in March after which the analysis of the results is carried out. The final report of the study is prepared in May.

1.3 Structure of the report

This report contains two parts that are a literature review and an experimental study. The literature part comprises a literature review of the subject. First, board production process is described to gain an understanding of the water use in papermaking. Then, different water fractions are reviewed after which the quality of water is addressed. Last, internal water treatment technologies are presented. Additionally, Stora Enso Imatra Mills and Board Machine 1 are briefly introduced because they are examined in the experimental part. The production process of food service board is presented from the stock preparation to the drying section because the interest is on water systems, and the wet end is where the water circulates. Also, broke handling is addressed through water purification.

The experimental study presents a case study of water consumption in an existing board machine and provides possibilities for optimization of water use. In the experimental study the specific water consumption of the board machine is determined, and the impact of water use optimization is addressed. The possibility of optimization of water use is determined with water quality analysis and filtration experiments.

In the end of the thesis, the main conclusions are summarized. Additionally, suggestions for supplemental research are presented.

LITERATURE PART

2 WATER USE IN PAPERBOARD PRODUCTION

Water is essential in paperboard production. Water is used in transportation of fibers, chemicals and heat. Without water it would be exceedingly difficult to move fibers from one place to another whereas water carries pulp effortlessly. Water is used in heat exchangers to heat and cool processes and air, and it influences the formation of fiber bonds. Water is also used in washing of pulps and wires in order to remove impurities and enable stable and continuous production processes. Water used in the board production can be divided into fresh water and circulation water, which is also known as white water, system. (Häggblom-Ahnger & Komulainen, 2005)

According to Kiviranta (2000) paperboard is a common title for different board grades that can be categorized as cartonboards, containerboards and special boards. Cartonboards comprises packaging boards, such as folding boxboard (FBB), solid bleached sulphateboard (SBS), white lined chipboard (WLC) and liquid packaging board (LPB). Containerboards contain linerboard and corrugation medium, and specialty boards include the rest of the board grades. The classification of board grades is based primarily on raw material used.

In this chapter, typical production process of board is briefly addressed followed by a review on fresh water use, white water system and wastewater generation. The review is performed to gain an understanding of the water use. For clarity, the water use in board production is summarized at the end of this chapter.

2.1 Board production

The production process of board is very similar to paper production process. The differences arise from different structures of web, basis weights and end-uses. Board typically consists of three plies and have a higher basis weight than paper. According to Häggblom-Ahnger & Komulainen (2005) basis weight over 150 g/m^2 is generally classified as board and under that as paper but there are exceptions. Due to resemblance of production processes further on also "papermaking" or other paper-relative terms can be used when discussing about production process and water circuits.

The purpose of the multilayer structure of board is to make the top and bottom plies hard and the middle ply bulky in order to achieve a strong structure cost-effectively. In addition, board can be coated or double-coated with pigment or plastic on both sides or on one side depending on the end-use. The process consists of stock preparation, web formation, pressing, drying, calendaring and finishing. Due to multilayer structure of board, generally separate stock flow and water systems are required in each ply. Separate systems enable the use of different stock components in different layers of board. (Häggblom-Ahnger & Komulainen, 2005; Kiviranta, 2000; Weise et al., 2008)

2.1.1 Stock preparation and wet end

Stock contains pulp, which can be chemical, mechanical or chemi-mechanical, and additives to alter the properties of board. Pulp is transported from the pulp mill to the board mill's stock preparation through pipelines or as dried bales. In integrates wet transportation is preferred to decrease the energy consumption in drying and processing the bales. Pulp is generally pumped at high consistency of 30 % or more to reduce the amount of water coming from the pulp mill (Stetter, 2006). The goal of the high consistency is to keep the water cycles in pulp and paper mill separate to prevent water soluble impurities from entering the paper mill circulation waters. In stock preparation pulp is diluted at desired consistency and chemicals are added. (Häggblom-Ahnger & Komulainen, 2005; Holik, 2006)

When stock is prepared web formation begins. Web formation includes a headbox and a wire section. The purpose of the headbox is to adjust the changes in pressure and consistency of the stock, create a turbulence to break down fiber flocs and to apply the stock as evenly as possible to the wire section. Stock from the headbox is mostly water, and the consistency is around 1 %. The function of the wire section is to infiltrate the excess water through the wire to enable the web to move into the press section. (Häggblom-Ahnger & Komulainen, 2005; Holik, 2006) Dewatering of the web is enhanced with vacuum systems in the wire section (Räisänen, 2008). A vacuum system comprises a suction box, a couch roll and in the newer applications a curved vacuum box.

Generally, over 95 % of the water from the headbox is removed at the wire section. In addition, 30 - 40 % of the solids coming from the headbox passes the wire while the rest stick to the forming web (Lacorte et al., 2003). In order to break down and prevent the formation of flocs, hydrodynamic forces are caused in the wire section to the forming web. Wire section determines the structural properties of the board which is why it is essential to manage the dewatering and hydrodynamic forces that affect the formation of the web. (Häggblom-Ahnger & Komulainen, 2005; Holik, 2006)

The dry content of the web coming from the wire section is around 15 - 20 % and after pressing the dry content rises to 40 – 55 %. It is significantly more economical to remove water from the web by pressing than by evaporating which is why the goal is to achieve a high dry content at the pressing section before the drying section. Wet pressing is based on pressing the web between two rolls, a nip, to reduce the volume of the web. When the volume of the web decreases water transfers to the felt because the pressure is lower at the felt. Dewatering at the nip is based on hydraulic pressure. (Häggblom-Ahnger & Komulainen, 2005) Vacuum systems are adapted to dewatering also in press section (Räisänen, 2008).

The exiting water at wire section, press section and drying section is illustrated in Figure 2. As can be seen, even over 97 % of water is removed at wire section, over 2 % at press section and under 1 % at drying section. Drying is further discussed in the next chapter.

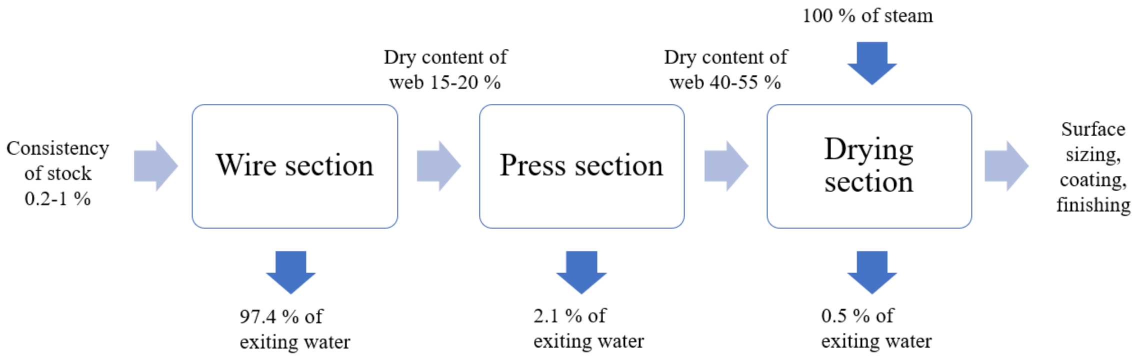

Figure 2 Dewatering of the web at wire, press and drying sections (adapted from Karlsson & Paltakari, 2010; Häggblom-Ahnger & Komulainen, 2005).

2.1.2 Dry end and finishing

After pressing, the web is dried in the drying section. Drying section consists of drying cylinders that are heated with steam to remove water via evaporation. The costs of drying the web with steam are five-times higher than by pressing the water at pressing section (Valmet Oy, 1997). The steam pressure of the first cylinders is low in order to prevent the wet web from sticking to the cylinders, and the pressure rises proceeding the section. The goal of the drying section is to dry the web to enable the surface sizing, coating and finishing to customer's requirements. (Häggblom-Ahnger & Komulainen, 2005)

Surface sizing is typical for board production to achieve high surface bonding strength, stiffness, better absorption properties and to prevent dust formation. In surface sizing the surface size which is usually cooked starch is laid on the surface of the dried web, and the web is led through drying cylinders to enable calendaring. The purpose of calendaring is to enhance the properties of the board in order to reach the standards. With calendaring fluctuations in thickness can be adjusted and smoothness and glossiness can be enhanced. However, calendaring has also negative impacts of the quality which is why it must be managed carefully. (Häggblom-Ahnger & Komulainen, 2005)

The last part of a board machine is a reeler where the produced board is rolled on a reeling drum for finishing treatment. Generally, board is first trimmed in smaller board rolls at winder and then send to further treatment or directly to customer. Trimmed rolls can be coated with plastic or trimmed again to sheets. Another option is to coat the board before trimming to rolls which is usually carried out with on-machine coating. Generally, plastic coating is performed to trimmed rolls while pigment coating is performed on-machine or with a separate coater before trimming. (Häggblom-Ahnger & Komulainen, 2005)

2.1.3 Additives and fillers used in production process

Additives used in paper and board manufacturing and their place of addition in the manufacturing process is presented at Figure 3. The dosing of chemicals varies with different applications as well as the chemicals used. Additives and fillers are relevant when considering the circulation waters because all of the chemicals that do not attach to the web end up in white water. Conditions, retention aids and dosing affect the retention on the web and the amount passing to process water. The composition of white water is addressed in the Chapter 3.1.

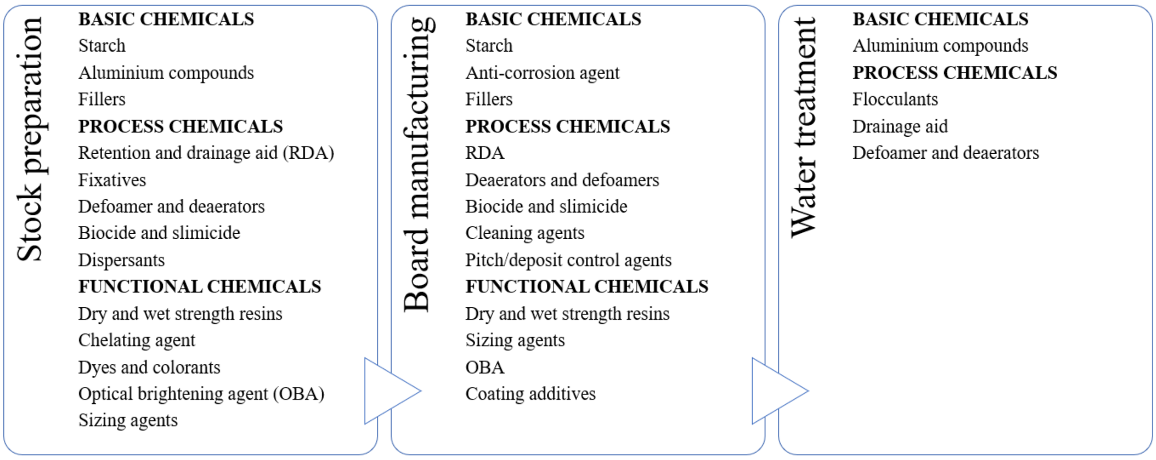

Figure 3 Additives used in paper and paperboard stock preparation, papermaking and water treatment (adapted from Auhorn, 2006; Häggblom-Ahgner & Komulainen, 2005).

Fillers are mineral pigments that fill the voids between fiber matrix in paper and board. According to Häggblom-Ahgner & Komulainen (2005) and Laufmann (2006) fillers typically used in papermaking are kaolin, talc, $CaCO_3$, TiO_2, $Al(OH)_3$, $CaSO_4$, synthetic silicates and organic pigments. According to Laufmann (2006) the purpose of fillers is to improve optical properties and smoothness of paper, to improve permanence and stability and to enhance printability. Häggblom-Ahgner & Komulainen (2005) argues the price of fillers that is generally lower than the price of fibers. Accordingly, applying fillers to papermaking is profitable both economically and via properties of paper. According to Shammas et al. (2010) the amount of fillers in white water can be over two times higher than in the stock due to low affinity of fillers for fibers.

2.2 Fresh water use

Fresh water is mechanically or chemically purified water generally from a river or a lake but also groundwater is utilized. Fresh water is purer than circulation waters which is why it is used in applications that require high purity such as showers in wire and press sections. Fresh water is brought to board machine heat recovery loop that is further described in Chapter 5. (Valmet Oy, 1997; Häggblom-Ahnger & Komulainen, 2005)

According to Huster et al. (1991) fresh water is brought to the process to ensure the quality of the product. Fresh water dilutes white water which decreases complications caused by accumulation of compounds in the water circuit. The reduction of fresh water use has been enabled with installation of fiber recovery units that purify the water from fibers which results to purer white water. Currently, the consumption or fresh water for multiply board is around 8-15 m^3/t_{board} (Weise et al., 2008) which indicates that more efficient purification technologies are required to treat the white water to increase the degree of closure. The consumption of fresh water varies among different paper and board grades. The properties and quality of the product affect the fresh water use as well as raw materials and chemicals used. High purity paper grades require pure water in order to maintain the quality while some board grades are not as responsive to water quality deterioration. According to Nuortila-Jokinen (1995), Weise et al. (2008) and Blanco et al. (2016) one of the issues regarding water circulation is buildup of thermal energy. Decreased fresh water consumption result to increase in temperature and requirement of process cooling. However, an increase of temperature of process water implies reductions of energy consumption in warming the water.

Fresh water is used in producing and diluting chemicals, as cooling water and as sealing water in pumps and mixing devices. Also, steam used in drying is produced from fresh water at the power plant and transported to board mill. (Valmet Oy, 1997) Fresh water is applied in these applications because the quality requirements of water are high, and fresh water is purer that white water. Water recycling is applied in these applications, but fresh water is brought to circuit to ensure the quality. For instance, according to Honkamaa & Käki (2008) clean fresh water with temperature of 20 to 30°C is recommended for sealing water purposes in order to prevent corrosion and enrichment of impurities in the structures. In addition, these targets require certain amount of water to function properly. For instance, reduction of water in chemical dilution affects the concentration, and lack of sealing water may cause damage to equipment. Water reduction actions in these targets should concentrate on increasing water recycling and by that, reduce the fresh water consumption and effluent generation. (Dahl, 2008)

2.3 White water system

White water comprises a significant amount of water used in board production. As mentioned in Chapter 2.1.1, over 95 % of water coming from the headbox is removed at the wire section. The water filtrating through the wire and shower waters from the wet end are called white water. White water contains fibers, fillers and other chemicals from the production process of board. White water is collected into wire flumes and returned to the wire pit where it is used to dilute thick stock. This water circulation system, or white water system by another name, that separates the excess water from the stock is called short circulation. (Häggblom-Ahnger & Komulainen, 2005; Weise et al., 2008; Dahl, 2008)

Short circulation comprises also stock circulation to clean the stock from impurities and to ensure even consistency of the stock. Consequently, white water affects the stock quality, and variations in white water can be observed from the product. Diluted stock from the bottom of the wire pit is pumped to centrifugal cleaning plant where impurities are removed with hydro-cyclones. The water used in dilution at higher stages of cleaner cascade is generally filtrate from fiber recovery unit, a disc filter. Purer water fraction improves efficiency of separation and reduces fiber loss. (Weise et al., 2008) Before feeding the stock from the centrifugal cleaning plant to headbox air is removed by deaeration and stock is screened. There can be a short circulation for every layer of the board to enable the use of different fibers, fillers and chemicals dosing. (Häggblom-Ahnger & Komulainen, 2005; Weise et al., 2008)

The main water circulation system, long circulation, comprehends the excess water that is collected from the overflow of the wire pit to the circulation water tanks and reused in the process. Also, clear filtrate and super-clear filtrate (SCF) from fiber recovery are stored in water towers. If there are two water storage towers, one can be dedicated solely for clear filtrate and the other may contain also white water. The distribution of water fractions to different towers enables the use of cleaner water in stable production while the cloudier water secures the water sufficiency. (Häggblom-Ahnger & Komulainen, 2005; Weise et al., 2008)

A simplified white water system is presented in Figure 4. Short circulation is marked with blue dashes and long circulation covers the entire flowsheet.

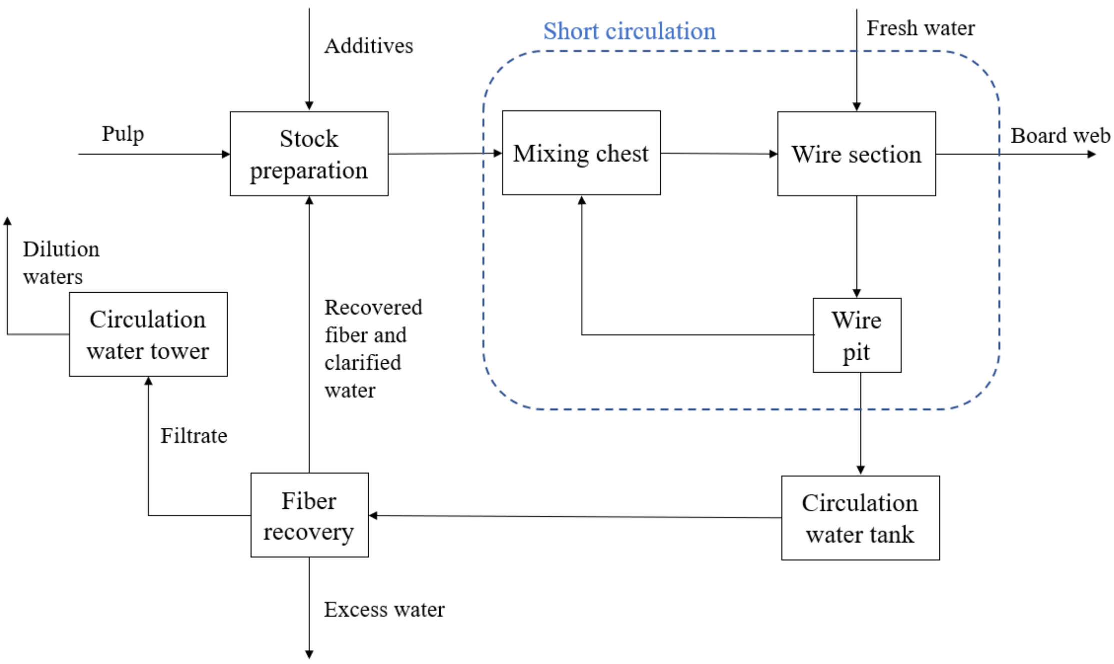

Figure 4 White water system (adapted from Dahl, 2008; Häggblom-Ahgner & Komulainen, 2005).

According to Weise et al. (2008) water circuits have a particular role during web breaks. When the web breaks, it is led to pulper. Pulpers are a part of the broke-handling system which is usually connected to the white water circuit. Broke comprehends all the board that is rejected at any stage of the production process at the mill. Broke is pulped with circulating water in pulpers and thickened in gravity decker where water is collected back to water circuit. During web breaks the formation of broke is greater than during continuous production and the water use in the process differs from the continuous production. In addition, more water is required for washing which increases the water consumption during web breaks. Commonly, fresh water is utilized excessively during web breaks due to increased requirement of water. Therefore, by accomplishing a functional white water cycle and with that a stable production process, fresh water consumption can be decreased.

2.4 Wastewater generation

Water that cannot be reused exits the process as wastewater. Additionally, there is continuously excess water present in the white water loop, and the excess water is constantly removed from the process as overflow. The excess water is formed due to the water content of the incoming stock that is dewatered to remove water and continuous addition of fresh water as described earlier. (Stetter, 20016) In integrated mills wastewater treatment is typically combined and wastewaters from all process stages are discharged at the same wastewater treatment plant. Commonly, activated sludge process is adapted to wastewater treatment in paper and pulp industry but other treatments, such as chemical treatment is utilized (Dahl, 2008).

Generally, wastewater generation at modern board mill is 5 to 15 m^3/t_{board} but there are variations (Seppälä, 2002). Hynninen (2008a) presents the wastewater discharge as 10 to 25 m^3/t_{board} for board mill producing folding boxboard and specifies, that the effluent discharge amounts are mill-specific and cannot be fully generalized. Stetter (2006) adduces effluent generation of 3 to 5 m^3/t_{board} as the maximum limit of system closure for board and from 8 to 10 m^3/t_{paper} for graphic paper grades that have more strict quality requirements. Decreasing the water use below these limits would lead to accumulation of detrimental substances which could be observed as runnability problems, odor problems and at the product quality that are discussed later on in Chapter 3.1.1 and Chapter 3.1.2.

2.5 Summary of water use

A simplified illustration of the main water circuits in paper mill is presented in Figure 5. For simplicity, fiber flows are marked with dashes and reclaimed water from effluent treatment plant with blue. As can be observed, there are three water treatment units that are fresh water treatment plant, effluent treatment plant and internal treatment units. It has to be notified that reclaimed water is not utilized in every mill. However, applying tertiary treatment to gain reclaimed water that can be utilized at the mill is a significant water use optimization possibility.

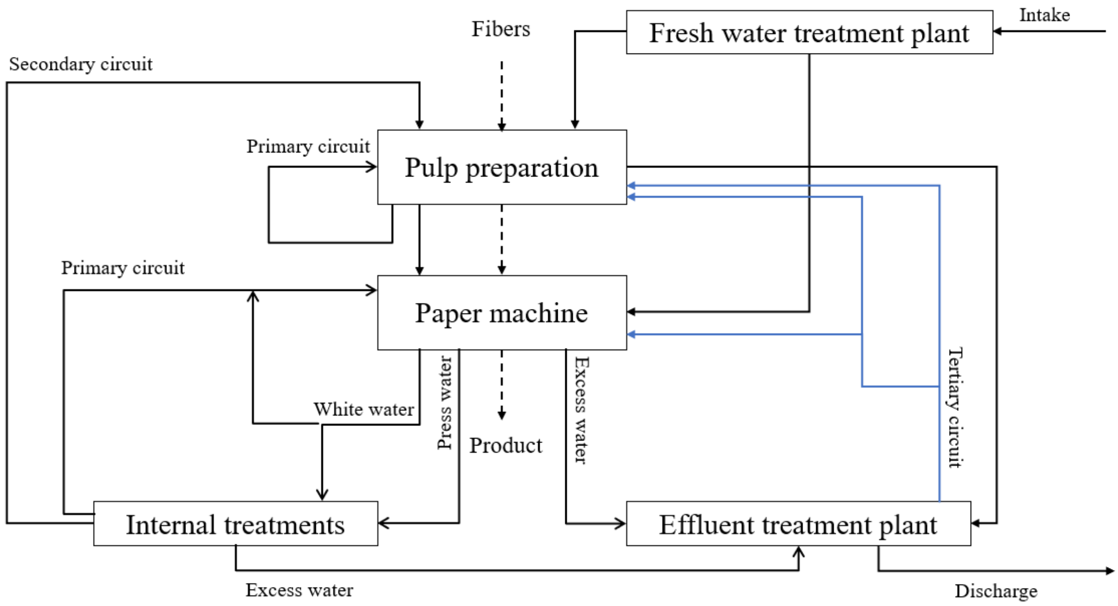

Figure 5 Water circuits in paper mill (adapted from Blanco et al., 2016).

Water reduction actions in papermaking should concentrate on white water system because it comprises all the water transporting with the stock, stock diluting waters and waters from fiber recovery. By concentrating on the white water system, generation of wastewater and fresh water consumption can be minimized. A counter-current water flow is applied in papermaking meaning that fresh water is added at the paper machine where the water quality requirements are at its highest and excess water is send backwards to previous process stages where the quality requirements are not as high. In addition, water is discharged at its lowest quality. By applying the counter-current flow water can be used more efficiently and fresh water consumption can be decreased. (Stetter, 2006)

3 WHITE WATER

This chapter discusses the composition of white water and the quality requirements of reused water in board production. White water is chosen for the observation because it comprises the majority of water used in papermaking and it is the most significant water fraction in the mill along with fresh water (Stetter, 2006). Analysis methods to measure the properties of circulation waters are reviewed. In addition, the impact of water quality to final product is briefly addressed.

3.1 Composition of white water

All compounds that do not attach to the web end up in white water. Impurities can originate from pulp production, fresh water or additives. Due to reduction of fresh water consumption and increased circulation of process water, enrichment of disturbing substances occur. Consequently, the quality of process water that is purified white water is lower than fresh water (Stetter, 2006).

White water contains small fibers, fiber debris and chemicals, such as retention polymers, filler pigments, defoaming agents, wet strength agents, fixatives and biocides (Shammas et al. 2010). The solids content of white water is around 1500 to 2000 mg/l due to infiltration of 30 to 40 % of the fibers from the headbox through the wire (Lacorte et al., 2003). One way to categorize substances in white water is presented in Figure 6 where types of compounds are presented with examples of each type.

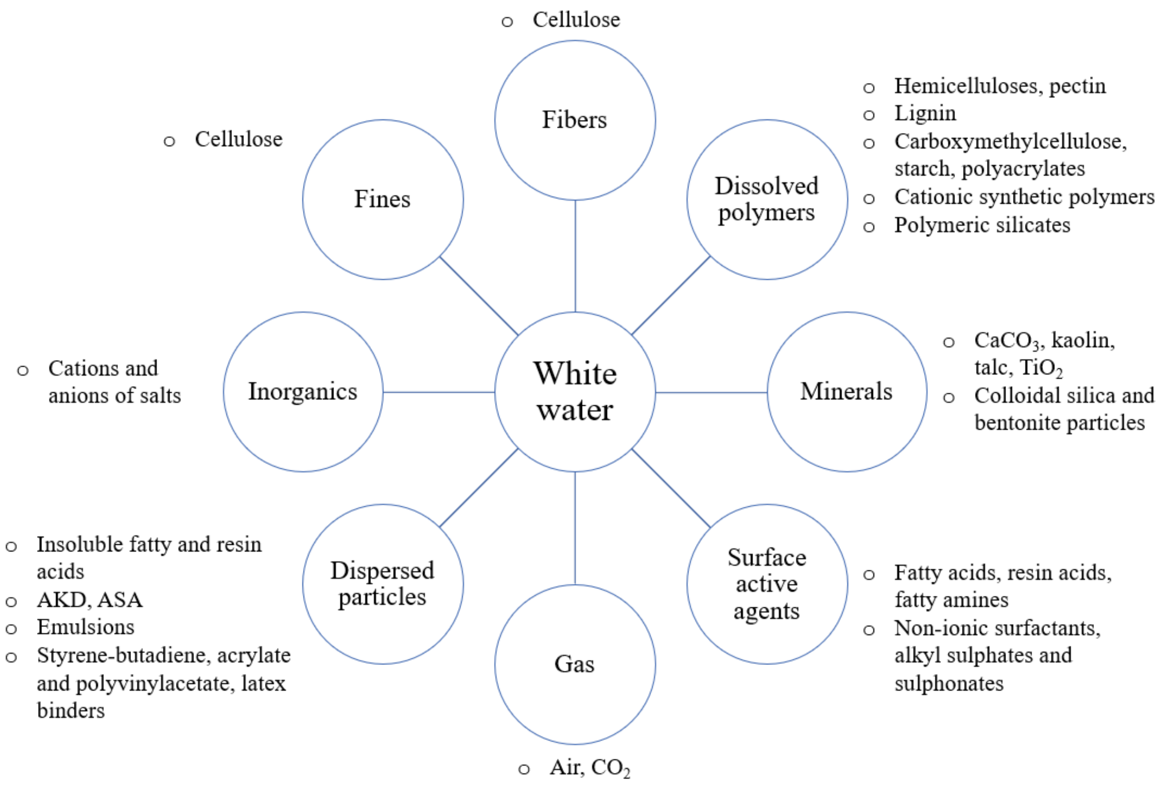

Figure 6 Composition of white water (adapted from Knuutinen & Alén, 2007; Stenius, 2000).

As Stetter (2006) expresses water is the most important component of papermaking after fibers. Due to this, it is obvious that impurities in water cause problems in the process and deteriorate the quality of paper. As described earlier, papermaking is quite a complex process where different process phases are connected to each other via water. According to Knuutinen & Alén (2007) enriched white water affects the wet end chemistry which is highly affected by condition changes. Changes in pH, alkalinity, temperature and chemical composition alter the papermaking chemistry which affects the entire process. These changes can be observed in retention of fibers and chemicals to the web, dewatering of the web and total efficiency of the process. Consequently, they can be observed at the final product. The substances in white water can be divided into suspended solids (SS) and dissolved and colloidal substances (DCS) which are further addressed below. Detrimental substances are a subgroup of DCS.

3.1.1 Suspended solids (SS)

Suspended solids (SS) are particles that do not dissolve in water but remain in suspension. According to Nuortila-Jokinen (1995) SS are particles over 1 µm in size. SS comprises mostly fibers and fillers, and the first phase of treatment targets to remove SS. Mechanical or chemically enhanced mechanical treatment is generally used in separation of SS from water.

Accumulation of SS causes clogging of wire and felt which reduces the drainage through the cloth which may lead to ununiform structure of the web. Due to wire section's major effect on board properties the quality of board deteriorates with accumulation of SS and eventually a new cloth is required to reach the quality standards. (Huster et al., 1991) The wet end showers are exposed to clogging with high SS loads in water. The capacity of fiber recovery unit decreases with high SS load, and the function of the whole water circulation system is threatened when less water is released to storage tanks. Dirt and deposits are formed to the board machine structures and falling of dirt and deposits to the forming web can be detected in product quality. In addition, the probability of web breakage increases. (Nuortila-Jokinen, 1995; Weise et al., 2008; Blanco et al., 2016)

3.1.2 Dissolved and colloidal substances (DCS)

Dissolved and colloidal substances (DCS) can be divided into detrimental substances, organic dissolved and colloidal substances and inorganic dissolved substances (Weise et al., 2008). Nuortila-Jokinen (1995) classifies dissolved substances to particles under 50 - 100 nm in size and colloidal to over 50 - 100 nm. However, the classification is not strict due to changes in size of particles during the process.

Detrimental substances are a variety of non-ionic and anionic DCS that cause harmful impacts throughout the production process. Detrimental substances originate from wood, fresh water, additives, broke and recycled paper or board. Anionic compounds are called anionic trash and comprise anionic oligomers and polyelectrolytes. Non-ionic compounds are hydrocolloids. (Stetter, 2006; Weise et al., 2008)

Common detrimental substances in process water and the origin of each chemical compound are presented in Table I. As can be observed, many of the compounds originate from pulp. For instance, lignin derivates and hemicelluloses originate from chemical and mechanical pulp. Especially mechanical pulp is a major source of detrimental substances because it is not treated with chemicals such as chemical pulp is and the detrimental substances are not dissolved. According to Häggblom-Ahgner & Komulainen (2005) in order to reduce the presence of detrimental substances in the board machine the pulp must be delivered at high consistency to minimize the transition of dissolved and colloidal compounds.

Table I Detrimental substances and the origin of each substance (adapted from Stetter, 2006; Weise et al., 2008).

Chemical compound	Origin of the compound
Sodium silicate	Peroxide bleaching, deinking, recovered paper
Polyphosphate, polyacrylate	Filler dispersing agent
Organic acids	Pitch dispersing agent
Carboxymethylcellulose	Coated broke
Starch	Recovered paper, broke, strengthening agents
Humic acid	Fresh water
Lignin derivates, lignosulphonates, hemicelluloses, fatty acids	Chemical and mechanical pulp

Enrichment of DCS impacts the wet end chemistry. In comparison to SS, DCS adduce more challenges to papermaking process because the challenges are more extensive and far-reaching. Dissolved substances are not removed in fiber recovery which makes the accumulation a serious threat with high closure of water cycle if proper advanced treatment is not utilized. DCS are the reason why decreasing fresh water consumption near to zero is challenging (Stetter, 2006). With high degree of water cycle closure the content of DCS is high which increases the problems caused by them. Consequently, with low specific effluent the specific load of chemical oxygen demand (COD) in the paper is at its highest. So, with low effluent discharge the load of COD in the product is higher than with higher effluent discharge. The COD load decreases by increasing the specific effluent when also the COD load in the effluent increases.

Stetter (2006) describes that the influence of detrimental substances can be detected as reduction in board machine speed. Major factors affecting the machine speed are drainage and drying which performance is deteriorated by detrimental substances. Other problems caused by detrimental substances are reduced efficiency of additives, reduced strength properties, impaired optical properties, poor sizing and bad odor. In addition, detrimental substances cause foaming and impact deposit formation. Consequently, detrimental substances determine the reusability of water and set limitations for reducing fresh water consumption. When reducing effluent generation by increasing water circulation detrimental substances begin to load on the paper instead of being discharged.

Dissolved inorganic substances, mostly salts, cause corrosion and formation of scale. Organic substances enhance the growth of microbes by providing nutrition. Growth of microbes induce the formation of slime that accumulate on the walls of pipes and process units. Pieces of slime can tear off from the process equipment and deposit on the forming product. Propagation of microbes causes smell formation and impact the color of water which might impact the product appearance as marks or tears, for instance. According to Alakomi et al. (2002) the environment of paper machine is beneficial for microbes growth due to warmth and humidity along with available nutrition. Both scale formation and microbial activity contribute to formation of deposits. In addition, microbial activity threatens the hygiene of the product and increased microbial content in the product might lead to disqualification of the product (BREF, 2015). By controlling the microorganisms in the paper machine environment, many problems related to runnability and product safety can be avoided. (Weise et al., 2008; Stetter, 2006; Auhorn, 2006; Blanco et al., 2016; Huster et al., 1991)

3.2 Analysis methods to measure the properties of white water

The quality of white water is generally measured with the total suspended solids (TSS), the total organic carbon (TOC), the chemical oxygen demand (COD) and the biochemical oxygen demand (BOD) (Nuortila-Jokinen, 1995). Also, nutrients, mostly nitrogen (N) and phosphorous (P), and AOX, that is adsorbable organic halogen that is mostly the amount of chlorine, are measured from the effluents (Hynninen, 2008a). TSS measures the amount of total suspended matter in water and TOC the amount of organic carbon in the sample. COD measures the amount of oxygen required in chemical decomposition of waste. BOD measures the amount of oxygen required in microbial decomposition of waste. BOD is generally reported as BOD_5 that is measured over a five-day-period but also other time periods, such as 7, 20 or 24 days, are used. (Hynninen, 2008a)

The chemical composition of effluents and white water varies depending on raw materials used and the compounds present have not yet been fully identified. Due to complexity of wastewater the so-called sum-parameters mentioned earlier provide efficient method for water characteristics analysis because they provide a comprehensive measure of the compounds present in the water.

Other determinations made from circulation waters are ash content, conductivity, cationic demand or anionic trash, turbidity, total extractives, total carbohydrates and microbial activity. Table II summarizes the common parameters that are measured form paper or board mill water and presents the measured component or components and an analysis method for each parameter. Besides the methods presented in Table II, also chromatographic and spectroscopic methods can be applied to identify specific compound groups (Knuutinen & Alén, 2007).

Table II Common determinations from paper/board mill white water (adapted from Knuutinen & Alén, 2007).

Parameter	Measured component	Analysis method
TDS	Organic and inorganic compounds	Evaporation, gravimetry
COD	Organic compounds	Dichromate oxidation
BOD	Degradable organic compounds	Biochemical oxidation by bacteria over a time period
TOC	Organic compounds	Catalytic oxidation, carbon dioxide determination
Ash	Inorganic compounds	Combustion, gravimetry
Conductivity	Salts	Electric conductivity
Cationic demand, anionic trash	Anionic polymers	Titration with cationic polyelectrolyte
Turbidity	Suspended particles	Light scattering
Total extractives	Lipophilic compounds	Extraction, gravimetry
Total carbohydrates	Mono-, oligo- and polysaccharides	Colorimetry with orcinol
Microbial activity	The presence of microbes	Colony forming unit

White water that is discharged from paper mill is led to water treatment plant. Typical characteristics of paper mill effluent, or discharged white water, are presented in Table III. Gupta and Gupta (2019) and Lacorte et al. (2003) propose general values for paper mill white water discharged from the paper mill. Hynninen (2008a) presents effluent loads for folding boxboard calculated for effluent discharge of 10 - 25 m^3/t_{board} with assumption of 1 metric ton of board is produced. Elliot and Mahmood (2007) present mean values for multiple paper mills producing fine paper from chemical pulp. From the values Nassar (2003) presents the former ones are for paper machine effluent and the latter for effluent from fiber recovery unit both from a mill using pulp made of wastepaper. The values of Dilek and Gökçay (1994) are from paper machine producing cigarette paper from hemp-based pulp. The values of Yen et al. (1996) are from effluent from two paper machines producing printing and writing paper from bamboo. Values are presented according to each reference in mg/l. Elliot and Mahmood (2007) presented phosphorous as PO_4^{3-} while other measures are of total phosphorous. Nassar (2003) presented total solids which covers TSS and total dissolved solids (TDS).

Table III Papermill white water characteristics. In upper indexes (a) refers to PO_4^{3-} and (b) to total solids concentration. All values are presented in mg/l.

Parameter / Source	**TSS**	**COD**	**BOD**	**N**	**P**
Gupta & Gupta, 2019	645	1116	641	-	-
Lacorte et al., 2003	17 – 40	1900 – 3200	770 – 1800	3 – 13	0.5 – 1.8
Hynninen, 2008a	200 – 1000	160 – 600	80-400	2 – 10	0.3 – 0.8
Elliot & Mahmood, 2007	212	505	205	-	1.0 [a]
Nassar, 2003	1370, 600 [b]	1400, 1060	500, 400	-	-
Dilek & Gökçay, 1994	1032	-	240	2.4	0.9 [a]
Yen et al., 1996	503	723	170	-	-

As can be seen from Table III, water characteristics vary depending on the type of produced paper or board, water system and water treatment technologies. However, the TSS, COD and BOD prove that papermill white water must be treated before discharge or reuse. The major difference in the presented values is the TSS of Lacorte et al. (2003) that is much lower than in other references. Because the value is so low it is most likely presented for white water that is treated in fiber recovery unit or some other treatment. The similarity between the presented values can be observed with concentrations of nitrogen and phosphorous that are low with every reference.

3.3 Quality requirements for reusable water

Reusable water quality is measured as suspended solids load in order to prevent clogging of shower nozzles. Generally, water is screened before feeding to showers and depending on the application different orifices of screens are used. The goal of screening is to capture particles from the water. According to Weise et al. (2008) water with TSS content under 50 mg/l can be used in fresh water applications. The TSS content for brush type showers is from 200 to 500 mg/l and for cleanable showers over 500 mg/l.

Besides SS also other parameters impact the reusability of white water. DCS effect the wet end chemistry and are measured as conductivity, for instance. The quality requirements of water in high pressure showers are presented in Table IV according to Blanco et al. (2015). It can be observed that Blanco et al. (2015) considers the maximum of 5 mg/l TSS usable in high pressure showers while Weise et al. (2008) argues the maximum of 50 mg/l is usable in fresh water applications including the high pressure showers. It can be concluded that the limits are not unambiguous and depend on the application as well as the quality requirements of the product. With high quality paper the water has to be purer than with board that has lower quality requirements.

Table IV Limiting values for water quality in high pressure showers in paper machine (adapted from Blanco et al., 2015).

Parameter	High pressure showers
pH, -	6.5-7.5
TSS, [mg/l]	5
TDS, [mg/l]	300
Conductivity, [mS/m]	50
Color, [PCU]	30
COD, [mg/l]	5
Hardness, [mg($CaCO_3$)/l]	200
Alkalinity, [mg($CaCO_3$)/l]	100
NH_4^+-N, [mg/l]	0.5
Si, [mg(SiO_2)/l]	5
Fe, [mg/l]	0.1
Mn, [mg/l]	0.05

4 INTERNAL WATER TREATMENT TECHNOLOGIES

Recycling water in pulp and paper industry is referred as closing the water cycle. Before closure of water cycle the fresh water consumption was around 130 m^3/t_{board} while currently it is around 8 - 15 m^3/t_{board} according to Weise et al. (2008). As mentioned earlier, in order to close the water cycle more on-site treatment must be adapted to purify the process waters and ensure the stable production. (Valmet Oy, 1997) According to BAT for production of pulp, paper and board (BREF, 2015) on-site treatment technologies, that are referred as kidneys, are coming more and more common in white water treatment.

The measures to reduce water consumption are divided into four groups in reference document on BAT for production of pulp, paper and board (BREF, 2015). Two of which target the water treatment with advanced white water treatment and on-site process water treatment. The other two measures are systematic water management and fresh water savings and substitution. Internal water treatment provides more feasible alternative than traditional external treatment. Blanco et al. (2016) indicate that paper mill white water represents a large fraction of paper mill effluent if it is not recirculated back to the process. Consequently, white water treatment offers cost-savings due to better targeted treatment, savings in raw material when fibers are recovered and less fresh water is required and reduction of energy consumption in fresh water treatment, pumping and heating. Targeted treatment refers to concentrating on specific substances in the mill’s wastewaters rather than the wastewater mixture from various sources.

The goal of the treatment of white water is to purify water to be reused in the process without complications and to return solids to the process. Consequently, water purification techniques can be divided into fiber recovery and water polishing. Fiber recovery units are referred as save-alls. In addition to fiber also fillers are recovered in save-alls. According to Nassar (2003) a few general types of save-alls can be recognized. These can be divided into revolving screen or cylinder, vacuum filter, clarification and flotation. Blanco et al. (2016) specifies that generally disc filter or dissolved air flotation (DAF) is applied as a save-all. Shammas et al. (2010) state that typically 30 to 60 % of oxygen demand can be reduced in a save-all while some fibers, starches, gums and dyestuffs end-up in the filtrate. Generally, fiber recovery in a save-all is the first step of white water treatment followed by advanced treatment depending on the desired purity of water. White water treatment decreases the board mill effluent and increases the quality of effluent by solids recovery. (Valmet Oy, 1997; Weise et al., 2008; Choi et al., 2003)

In this chapter different internal treatment technologies are presented starting from filtration and screening and continuing to flotation and clarification, physicochemical technologies, biological treatment and advanced treatment technologies. Separation methods for different sizes of impurities are presented in Figure 7. Filtration techniques for each particle size are presented starting from the largest particles method can be used for. However, the division is not strict and for instance, conventional filtration can be used for separation of fines and polysaccharides and ultrafiltration is capable to remove sugars. The separation can be adjusted with pore size and cut-off value of membrane.

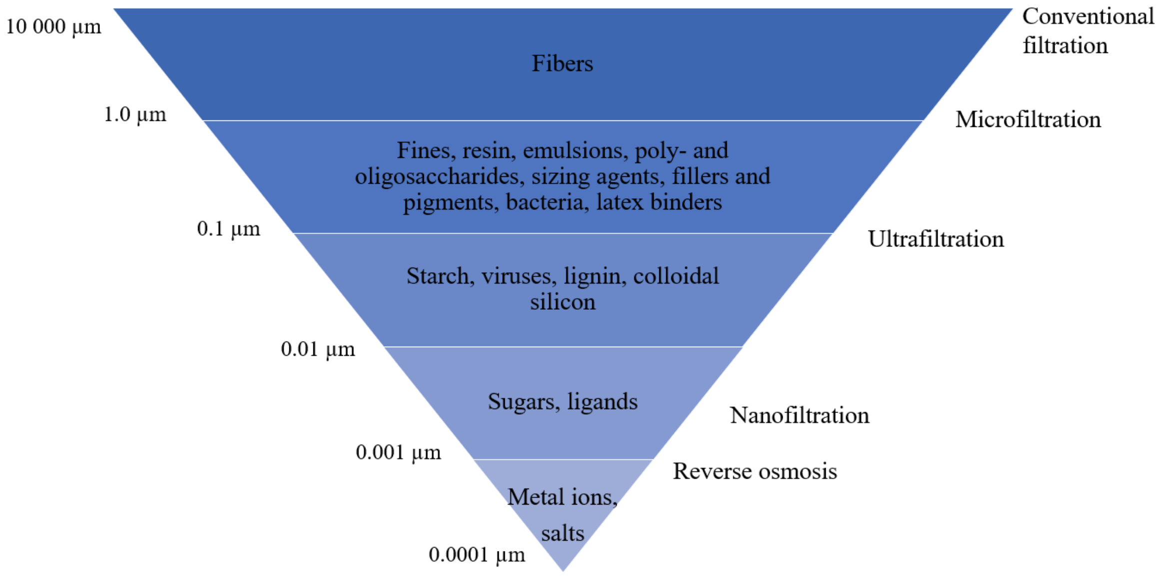

Figure 7 Separation methods for different particle sizes, the largest particles being on the top and smallest at the bottom. Technologies are presented from the largest particles the method can be used for. (Adapted from Hynninen, 2008a; Weise et al., 2008)

In addition to methods presented in Figure 7 evaporation can be applied for separation of all of the impurities being the most efficient with smaller particles. Due to high demand of energy, evaporation has been applied only to treating small volumes of contaminated water. Lower energy consumption of filtration encourages to utilize filtration instead of evaporation according to Nuortila-Jokinen (1995). (Hubbe, 2007)

4.1 Filtration and screening

Filtration is broadly applied in paper mill white water treatment. Filtration can be adapted after screening to achieve a higher purity of water, and multiple filtration techniques can be combined for the same reason. In addition, filtration can be followed by screening depending on the application. By removing coarse particles first and smaller ones after that the clogging of screen or filter media can be avoided.

4.1.1 Screens and strainers

According to Sparks & Chase (2016) screens and strainers are widely utilized filtration technologies due to simplicity and effectivity. The difference between screens and strainers is that strainers typically restrain oversized particles and in addition to that, screens might also be applied in size classification of particles. Screens are generally made from metal but also other materials, such as plastic, can be applied. In papermaking screens and strainers are generally used as police filters in water and stock suspensions. Police filter, or safety filter by another name, is a title for a filter whose goal is to guarantee the quality of filtered flow by restraining solid matter. Police filter is usually applied between disc filter and shower water storage to further polish the water from fibers. Police filter offers the last treatment for water before storage or feeding to shower water nozzles, for instance. There are two general types of police filters adapted at paper machine that are white water filter and bow screen. (Valmet, 1997)

Bow screen, or curved or inclined screen, is applied to treat the water mechanically and retain fibers from it. Screens can be applied in multiple locations such as before water storage tank or shower water nozzles as mentioned earlier. Additionally, according to Weise et al. (2008) screens can be used in fiber recovery and thickening. White water is passed through the screen and long, valuable fibers are recovered while small fibers and fillers pass through the screen (Shammas et al. 2010). There are different kinds of screens for different applications and the structure and the slot size depends on the application. So-called micro-screens are generally applied as shower water filter. Similar to filters also screens require washing in order to maintain operation and prevent clogging.

4.1.2 Disc filter and drum filter

Because also solid matter filtrates through the wire, circulation waters have to be purified form solids in order to prevent water quality deterioration. In addition, the water from the broke system is collected with a fiber recovery unit, and fiber suspension is dewatered at stock preparation. Generally, disc filter is utilized as a fiber recovery unit due to the ability to treat water of high solids content. Another similar filter to disc filter is a drum filter that is utilized in some applications as a save-all. Drum filter does not reach as high a capacity as disc filter due to higher filtration area of disc filter for the same floor space which is why disc filter is preferred. Fiber recovery units remove suspended solids but are incapable in removing DCS and salts efficiently. Other dewatering units used in stock preparation according to Holik (2006) are belt filters, twin wire presses, screw presses and screens. (Pitkänen et al., 2009; Weise et al.2008; Sparks & Chase, 2016)

Disc filter consists of multiple discs that are formed of segments covered of wire cloths. Discs rotate in a vat where the slurry is fed, and the wire cloth on the surface of the segment prevents the solids from entering the segment while water passes through the segment into a collection shaft. The fill grade, or the surface, of the vat where slurry is fed is crucial to maintain high due to decrease of capacity of the filter with too low a slurry level (Sparks & Chase, 2016). If the sectors are not fully covered with slurry in the vat, air manages to pass through the filter cloth in cake formation which decreases the filtration capacity. Pre-coating pulp, or sweetener, can be utilized in creating the fiber mat on the cloth to ensure particles' sticking to the cloth. Filtrate that infiltrates the wire cloth is collected to the shaft where it flows to the drop leg and vacuum is formed by the difference in height. The vacuum enhances the formation of fiber mat on the surface of the segment and clearer filtrate can be achieved. When the segment bypasses the surface of the slurry it is dried with air after which the fiber mat is detached from the surface by discharge showers and it drops into collection chutes and further to screw conveyor. In order to keep the wire cloth clean, the segment is washed before rotating back to the vat. (Pitkänen et al., 2009; Weise et al.2008; Holik, 2006; Sparks & Chase, 2016)

Drum filter consists of open roll that is covered with a filter cloth. In comparison to disc filter that contain multiple filter discs, drum filter has only one larger filter cloth through which the water infiltrates. The cloth can be also divided into panels instead of one-piece cloth for the entire filter surface (Sparks & Chase, 2016). Drum filter rotates in a vat filled with fiber suspension, and the fiber mat is formed on the outside of the filter drum. Fiber mat is collected from the drum and the cloth is washed with showers before rotating again. The filtrate is collected from the inside of the drum to a shaft. (Holik, 2006)

Three water fractions can be gained from disc filter based on the thickness of formed fiber mat and collection time. The fractions from disc filter are cloudy, clear and super-clear filtrates. Cloudy filtrate is collected at the beginning of the rotation cycle when the fiber mat is thin, clear filtrate in the middle phase and super-clear in the end when fiber mat is at its thickest. According to Weise et al. (2008) the solids contents of the filtrates can differ depending on the disc filter operation. For example, rotation speed affects the filtration capacity, and too high a rotation speed decreases the quality of filtrates. However, too slow a rotation speed can impact to discharge of filter cake and the capacity is low.

Typically, around 8 % of suspended solids from the white water transfer to cloudy filtrate, a little over 1 % to clear filtrate and under 0.5 % to super-clear filtrate (SCF). Cloudy filtrate contains solids over 50 mg/l to 400 mg/l and is usually recirculated back to the filter. The solid content of clear filtrate is under 50 mg/l and it is utilized in disc filter showers or pumped to the water storage towers. The purest filtrate from disc filter is SCF. SCF can be used directly as shower water due to its low solids content that can be under 10 mg/l but up to 20 mg/l. However, the treatment of SCF is required in some applications. Clear filtrate is the largest filtrate fraction from the disc filter. If only cloudy and clear filtrates are separated, clear filtrate comprises about 70 % of the entire filtrate. (Häggblom-Ahnger & Komulainen, 2005; Weise et al., 2008; Pitkänen et al., 2009)

4.1.3 Sand filter

Other filtration technique applied in paper and board mills is sand filtration. According to Hynninen (2008a) sand filtration is based on a sand bed through which the water flows and purifies. Sand filtration operates well with low solids content effluent and removes efficiently COD, BOD and nutrients. Washing of sand bed is mandatory in order to maintain the operation and prevent clogging of filter. Washing can be carried out continuously with separated compartments where filtration and washing can be implemented simultaneously. Weise et al. (2008) specifies that sand filters are mostly used in fresh water treatment and water preparation but Hynninen (2008a) adds that they can also be used in purification of recycled water. Sand filtration can be adapted to process water treatment or as tertiary treatment of wastewater.

Thompson et al. (2016) report reduction of 91 % of turbidity, 69 % of BOD, 49 % of COD and 100 % of TSS in laboratory scale tests for paper mill effluent treated with sand filtration. Filtration tests were also made with activated carbon and combination of sand and activated carbon, and it was concluded that sand filtration can be enhanced with addition of activated carbon. In addition to reduce TSS of water in sand filtration, activated carbon can remove metals, organic matter and some trace organics.

4.2 Chemical, physicochemical and biological treatment

Chemical precipitation is a common technology utilized in water treatment. In chemical precipitation dissolved impurities are precipitated with addition of a reagent. The added reagent forms insoluble compound with cations or anions to be separated from water. Chemical precipitation is used to remove soluble metals, phosphates and sulphates from water, and it can remove dissolved and colloidal particles. However, due to requirement of chemicals for precipitation the costs of treatment are high. Additionally, the effectivity of chemical precipitation is as its highest when used as pretreatment for other treatment technologies. (Gupta & Gupta, 2019; Nuortila-Jokinen, 1995)

Dissolved air flotation (DAF) is commonly utilized as a save-all in paper mills. DAF is based on air bubbles that attach to solid particles in water which makes the particles to float to the surface. Sludge can then be skimmed off from the surface and clarified water collected from the bottom. Flotation can be enhanced chemically to remove also dissolved and colloidal substances. Suspended solids removal in DAF can be as high as 80 - 98 % according to Blanco et al. (2016). However, high removal of DCS is not achieved with DAF, and the typical removal of colloidal substances is 10 - 40 % according to Weise et al. (2008). (Shammas et al., 2010; Weise et al., 2008)

Coagulation and flocculation are processes that aim to increase the size of particles to let them settle due to gravity. The difference between coagulation and flocculation is that coagulation is based on electrical charge of solid particle that is eliminated to promote the solid's ability to grow. In flocculation the agglomeration of particles is accomplished by rapid mixing. Generally, coagulation and flocculation happen simultaneously, and both processes can be enhanced with addition of chemicals, that are called coagulants or flocculants. (Gupta & Gupta, 2019) According to Gupta and Gupta (2019) chemical coagulation-flocculation is considered as pretreatment before sedimentation or filtration because solid matter is accumulated at the bottom of coagulation-flocculation tank. Hubbe et al. (2016) complement that by combining coagulation with DAF or membrane filtration the removal of impurities can be enhanced.

In clarification, or sedimentation, the separation is based on gravity. Contrary to DAF, in clarification solids are collected from the bottom and clarified water from the top. Clarification can be enhanced chemically with addition of flocculants. However, Shammas et al. (2010) conclude that the purification performance of chemically enhanced clarification is inferior to DAF. In addition, the space requirement of clarification is unfavorable. Consequently, clarification is generally replaced with DAF or other more efficient purification techniques.

Activated carbon is commonly used filter media in water treatment. The porous structure and high specific surface area of activated carbon propose good material for adsorption of impurities from water. Metals, organic compounds, including volatile organics, and chlorine can be removed from water with activated carbon. Activated carbon has been introduced in pulp and paper industry as tertiary phase of wastewater treatment. According to Thompson et al. (2016) activated carbon adsorption can be combined with sand filtration, for example, to enhance the removal dissolved inorganic and organic compounds. (Hubbe et al., 2016; Gupta & Gupta, 2019, Thompson et al., 2016)

Biological treatment is widely applied in wastewater treatment in pulp and paper industry. Generally, biological treatment is applied at wastewater treatment plant where activated sludge process is commonly utilized. A novel approach is to adapt in-mill biological treatment for white water purification. Alexandersson and Malmqvist (2005) piloted a combined anaerobic/aerobic process for white water treatment. High COD removal, majority of organic compounds removed, was achieved both in laboratory testing and in pilot trials. However, it was concluded that the variations in white water composition complicate the nutrient dosing and affect the removal of organic matter. In addition, sludge formation is unavoidable when biological process is in question and removal of suspended solids is required before water reuse. The purified water did not reach as high a quality as required in fine paper manufacturing, for instance, but it would be usable in fluting or liner production.

4.3 Advanced treatment technologies

In order to accomplish complete closure of water cycle advanced treatment technologies are required. Advanced treatment technologies can remove impurities more efficiently, so they do not accumulate in circulation waters. However, many advanced treatment technologies require pretreatment and are not efficient as only treatment but rather combined with other treatment methods. Advanced treatment technologies in pulp and paper industry consist mainly of membrane filtration, membrane bioreactors, ozonation and evaporation as described in reference document on BAT for production of pulp, paper and board (BREF, 2015).

4.3.1 Membrane filtration

Membrane filtration is based on filtration through a semipermeable barrier, a membrane. The driving force of the separation can be pressure, concentration gradient or electrical potential gradient (Bajpai, 2010). There are different kinds of membranes, and the properties of membrane affect the separation efficiency. In membrane filtration feed stream is divided into permeate and retentate or concentrate. Permeate is the fraction that infiltrates through the membrane and retentate contains the compounds that do not pass through the membrane. (Weise et al., 2008) Membrane filtration can be dead-end like conventional filtration or cross-flow filtration where tangential flow is applied on the membrane. Filtration methods are presented in Figure 8.

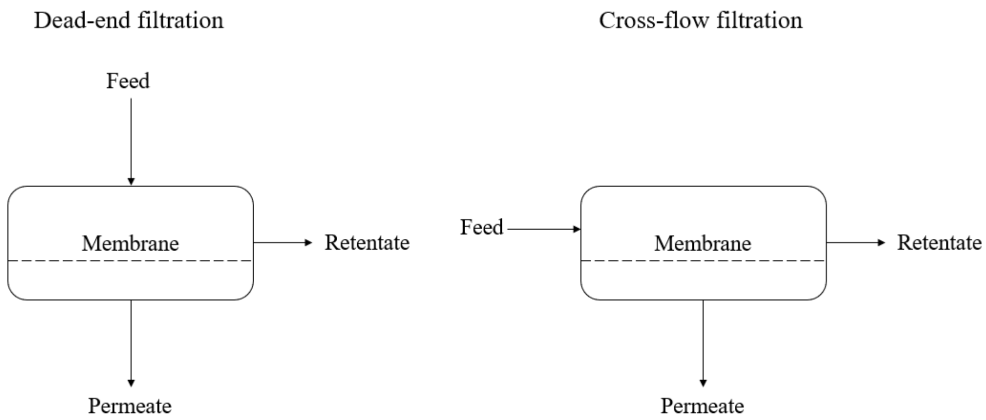

Figure 8 Illustration of dead-end and cross-flow membrane filtration. Membrane is drawn with dashes. Permeate passes through the membrane and can be collected to a separate container while retentate is retained on the membrane. (Adapted from Mulder, 1996)

Membrane technologies used in pulp and paper industry can be divided into microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). The driving force of these membrane processes is pressure difference. Typical operating pressures vary from 0.1 bar in MF to 100 bar in RO. The cut-off value as well as the components passing through the membrane decrease from microfiltration to reverse osmosis. Nuortila-Jokinen (1995) lists that with MF suspended solids, with UF dissolved and colloidal particles and with NF multivalent ions can be removed. In RO nearly only water molecules pass through the membrane which enables also the separation of inorganic salts. (Weise et al., 2008)

Typical characteristics of membranes used in pulp and paper industry water treatment are summarized in Table V. Other membrane properties include hydrophilicity and smoothness of membrane which effect to fouling ability. Mechanical durability and heat, pressure, abrasion, chemical and microbial resistance are desired in membrane. By the choice of membrane the aim is to achieve a high and steady flux, efficient separation and a long lifetime of membrane which leads to low operational costs. (Mulder, 1996)

Table V Characteristics of different membrane technologies (adapted from Weise et al., 2008; Mulder, 1996; Nuortila-Jokinen, 1995).

Characteristics	MF	UF	NF	RO
Pore size, [nm]	50 – 1500	1 – 100	< 2	< 2
Operating pressure, [bar]	0.1 – 2	1 – 5	5 –20	10 – 100
Membrane	(A)symmetric	Asymmetric	Composite	Asymmetric/ composite
Type	Porous	Porous	Porous	Non-porous
Charge	No	No	Yes/no	Yes/no
Separation is based on	Particle size		Differences in solubility and diffusivity	

According to Mulder (1996) the advantage of membrane technology is that membranes can be easily adjusted for every application due to adjustable membrane properties. The membrane material and type can be chosen for each application, and multiple membranes can be combined to reach the desired purification. In addition, membranes can be combined with different treatment technologies. The separation can be accomplished continuously and under mild conditions. Compared to evaporation, membrane filtration requires less energy and is able to achieve the same degree of purification. The main disadvantages of membranes are the membrane fouling, short lifetime and low flux or selectivity according to Mulder (1996). Fouling is caused by deposition formation on the membrane surface, clogging of pores and adsorption, and it decreases the flux. However, fouling can be prevented with a correct choice of membrane. The lifetime of membrane can be increased to some point with proper cleaning of membrane. (Weise et al., 2008; Nuortila-Jokinen, 1995)

4.3.2 Oxidation and advanced oxidation

Oxidation processes used in paper mill water treatment are presented in Figure 9. Oxidation processes can be divided into conventional, and further to biological and chemical, and to advanced oxidation. Chemical oxidation is based on oxidizing impurities into harmless substances and finally to CO_2 and H_2O. (Gupta & Gupta, 2019) Advanced oxidation processes (AOPs) are a variety of processes that are based on formation of hydroxyl radicals. Hydroxyl radicals have an unpaired electron which makes them highly reactive and their oxidative power high. Free hydroxyl radicals act as strong oxidants in water and destroy organic compounds completely. When comparing to other technologies mentioned in this chapter, AOPs stand out by complete destruction of contaminants while filtration, for instance, transfers the contaminants from one place to another. (Bajpai, 2010)

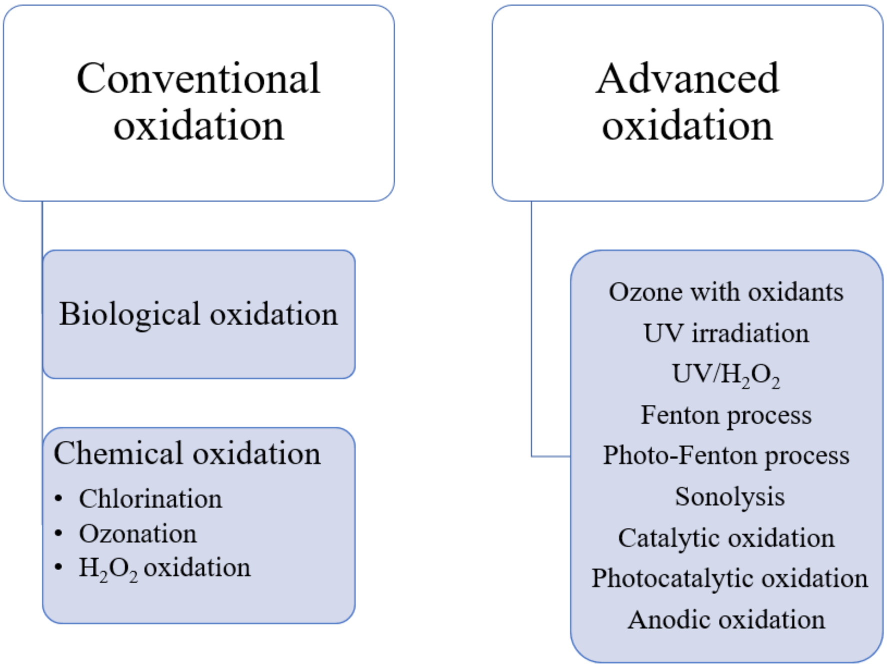

Figure 9 Different oxidation processes used in paper industry classified by type of oxidation (adapted from Gupta & Gupta, 2019; Hermosilla et al. 2015; Bajpai, 2010.)

Advanced oxidation processes have been proposed to pulp and paper mill effluent treatment as polishing treatment according to Hermosilla et al. (2015). Gupta & Gupta (2019) present ozonation as innovative technology in pulp and paper wastewater treatment. Ozonation and UV irradiation treatment can be used in water disinfection to replace chlorine and prevent formation of hazardous by-products (Hynninen, 2008b). Shammas et al. (2010) introduce UV treatment in white water treatment to polymerize dissolved solids, generally of biodegradable organic nature, into insoluble substances that can be separated via filtration. However, according to Hermosilla et al. (2015) UV treatment is not feasible as a stand-alone treatment. Higher removal of impurities can be achieved with combination of AOPs or other treatment technologies. Latorre et al. (2007) evaluate the performance of oxidation processes combined with biological treatment for packaging board mills' white water. It was concluded that combination of anaerobic, aerobic and ozonation treatment was able to remove organic compounds nearly completely.

Hermosilla et al. (2015) complement that multiple AOPs have proposed potential in pulp and paper industry water treatment at laboratory scale. However, due to high energy requirement of AOPs, stand-alone use of AOP is not desirable. In addition, the composition of water affects the performance of AOP via presence of hydroxyl radical scavengers or difficultly oxidizable compounds. AOPs have achieved high purification efficiencies but each case has to be specifically adapted to reach the full potential of the process. Pretreatment is often required to remove disturbing parameters, such as turbidity, from the water.

4.4 Summary of treatment technologies

Removal efficiencies of different treatment technologies are presented in Figure 10. The size of the ball corresponds to the removal efficiency of the parameter. The bigger the ball the better the treatment is to reduce the parameter in treated water. As can be observed, RO and evaporation reach the same removal efficiencies. The removal of salts is slightly deteriorated in NF and MF/UF is best adapted to TSS removal. Biological treatment effectively removes COD and electrodialysis salts. Combination of coagulation/flocculation and sedimentation/DAF has the lowest TSS removal efficiency compared to advanced technologies.

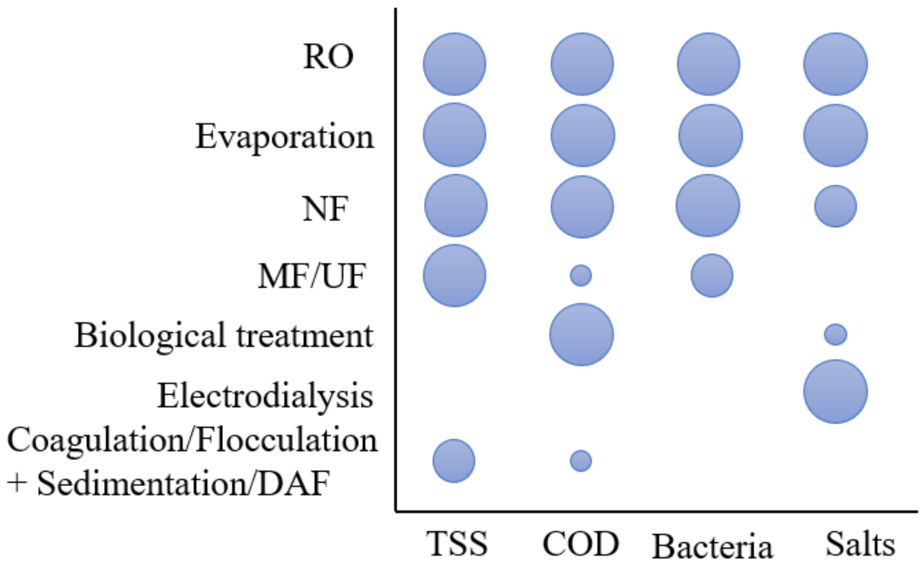

Figure 10 Qualitative removal efficiencies of selected treatment technologies (adapted from Blanco et al. 2016).

Discussed technologies are listed in Table VI to compare the advantages and disadvantages of each technology and to clarify the requirement of pretreatment and post-treatment. Post-treatment in this context illustrates whether further polishing treatment is required to achieve reclaimed water that can be reused. Naturally, treatment technologies can be used without post-treatment if the required level of purity is lower. Also, reduction of presented parameters from paper mill effluent or white water for each technology are listed.

Table VI Comparison of different water treatment technologies (adapted from Nuortila-Jokinen, 1995; Hubbe, 2007; Hubbe et al. 2016). Other citations are marked as follows: (a) Thompson et al., 2016, (b) Hynninen, 2008, (c) Weise et al., 2008, (d) Blanco et al., 2016, (e) Alexandersson & Malmqvist, 2005, (f) Amat et al., 2005, (g) Jamil et al., 2011, (h) Hermosilla et al., 2015 and (i) Bajpai, 2010.

Technology	Pre / Post	Reduction %	Advantages	Disadvantages
Sand filtration	No / Yes	TSS: 96-100 % [a] COD: 49 % [a] BOD: 69 % [a] Turbidity: 91 % [a]	Simple, cost-effective [a]	Clogging of filter with high loads [a,b]
Disc filter	No / Yes	TSS: 92-99.6 % [c]	Fiber recovery [c]	Does not remove DCS and salts [c]
UF	Yes / No	TSS: 99 % COD: 8-39 %	Easy to scale up, effective, easy to adapt	Fouling, expensive membranes
NF	Yes / No	TSS: 66-100 % COD: 42-91 %	Easy to scale up, effective, easy to adapt	Heavy pre-treatment often required, expensive membranes
Flotation	No / Yes	TSS: 80-98 % [d] COD: 77-84 %	Removes SS, enhanced with chemicals	High energy consumption, high operation cost, requirement of space
Chemical precipitation	No / Yes	COD: 19-46 %	Good pre-treatment for other methods	Expensive, does not remove all impurities (carbohydrates)
Biological treatment	Yes / Yes usually	Anaerobic COD: 42-70 % Anaerobic+aerobic COD: 77-86 % [e]	Effective BOD removal	Danger of poor dewatering, brightness loss, salt build up, sludge formation
Evaporation	Yes / No	COD: 98 %	High quality condensate reliably	High energy consumption, costs, fouling and scaling
AOP	Yes / No	O_3+UV COD: 18-99 % [f] BOD: 37-65 % [f] photo-Fenton TSS: 96.6 % [g] COD: 79.6 % [g]	Complete destruction of contaminants, non-selective, fast [g, h]	High energy consumption, composition of water affects the efficiency [h, i]

Different technologies produce different quality water and water quality can be adapted with combination of technologies. Also, process conditions and choice of chemicals, for instance, affect the removal efficiency. Reclaimed water, that is wastewater that has been purified enough to utilize again, could replace raw water or chemically purified water if the reclaimed water is purified with advanced methods. For instance, filtrate from the disc filter is not pure enough to replace fresh water but when the filtrate is treated with UF the quality might be adequate for such purpose. Generally, membrane technologies produce reclaimed water but, as been stated, the adaption of membrane technologies in paper industry require further investigation to discover the suitable membrane for the application. However, membrane processes generate a concentrate on top of the membrane that must be treated for reuse or disposal. AOPs can also remove persistent compounds and toxicity, caused mainly by pulping wastewaters, from water but the operating costs are high which is why membrane technologies are usually preferred (Hubbe et al., 2016; Gupta & Gupta, 2019; Bajpai, 2010).

5 BOARD MACHINE 1

Board Machine 1 (BM1) is one of Stora Enso Imatra Mills' four board machines. Stora Enso being a renewable materials company focuses on developing renewable, recyclable and low-carbon solutions to replace fossil-based materials. Imatra Mills is the largest producer of paperboard in Finland and one of the largest forest industry integrates in Europe. Imatra Mills is the greatest producer of liquid packaging board of the world and the largest unit of Stora Enso. Imatra Mills consists of two mill units that are Kaukopää and Tainionkoski. The yearly production of paper and board at Imatra Mills is around 1.2 million tons and of pulp 1.3 million tons. Paper and board are manufactured by five machines and coating is done by four coating machines. (Stora Enso, 2019; Stora Enso, 2021a; Stora Enso, 2021b)

BM1 is constructed in 1950 which makes it the oldest one at Imatra Mills, and it is located in Kaukopää. The capacity of BM1 is 195 000 t/a and the width of the machine is 4.4 m. The board produced in BM1 is three-ply Food Service Board (FSB) that is used in paper cups for hot and cold drinks and in food packaging. Basis weight distribution is from 170 to 330 g/m^2. The board is surface sized and often coated with a thin plastic layer. The main raw material of all three plies is birch pulp and chemi-thermomechanical pulp (CTMP) is used in some grades in the middle ply. Because the board is used in applications where it is directly in touch with food the most important properties of it are food-safety, odor and taste.

Additionally, optical properties, formability, stiffness and sealability are essential. (Stora Enso, 2019; Stora Enso, 2021a; Stora Enso, 2021b)

Water fractions coming to the mill can be divided into three water fractions. The flows are presented in Figure 11. Raw water and chemically treated water are fresh water with different quality. Raw water is used in warm water applications and as sealing and cooling water in different applications such as in suction pumps. Chemically treated water is used in dilutions of chemicals, high pressure showers, surface condenser where it circulates to warm water tank, and in heat control and sealing water in dilution headbox. (Marttinen, 2000) Pulp is transported to the mill where it is diluted with circulation waters. CTMP is diluted with water from the power plant and the consistency can be further adjusted with BM1 white water. Water discharged from the cycle is led to wastewater treatment plant.

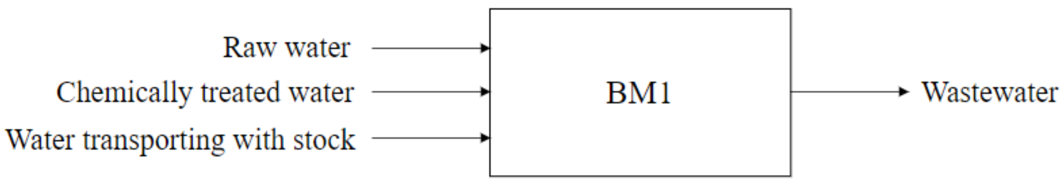

Figure 11 Incoming and outgoing water in BM1.

The wire section of BM1 comprises a two-ply headbox that forms the bottom and middle plies of the web on the wire and a regular headbox that forms the top ply. There is a short cycle for every layer when considering the mass cycle because there are centrifugal cleaning plants for every layer but the water from the wires are collected into two wire pits. So, water from the bottom wire where the bottom and middle plies are formed is collected to a wire pit and water from the top wire to another. There are a disc filter and two drum filters in the broke handling system of which only the disc filter is generally used during stable production. Disc filter used in BM1 is CDI Disc Filter from GL&V that is nowadays part of Valmet (Valmet, 2021a). There are 10 discs in the filter and the filtration area of one disc is 19.7 m^2. The material of filter cloth is steel. Three water fractions are collected from the disc filter as described in Chapter 4.1.2. Filtrates are collected into three drop legs from where SCF is transported to white water towers, clear filtrate is led to disc's showers and cloudy filtrate is returned to the filter. Excess clear filtrate is collected into white water towers.

There are two main water loops at BM1 that are white water loop and heat recovery loop. A simplified illustration of water loops is presented in Figure 12. Heat recovery loop is marked with dashes and the other loop is the white water loop. Black lines represent the main water flows and blue lines are so-called security flows that are not constantly used. The green line presents the water use optimization opportunity by applying SCF from the disc filter into heat recovery loop which would combine the loops. As the figure is a simplified diagram from the actual process, it does not contain all the water flows but just the ones discussed in this thesis.

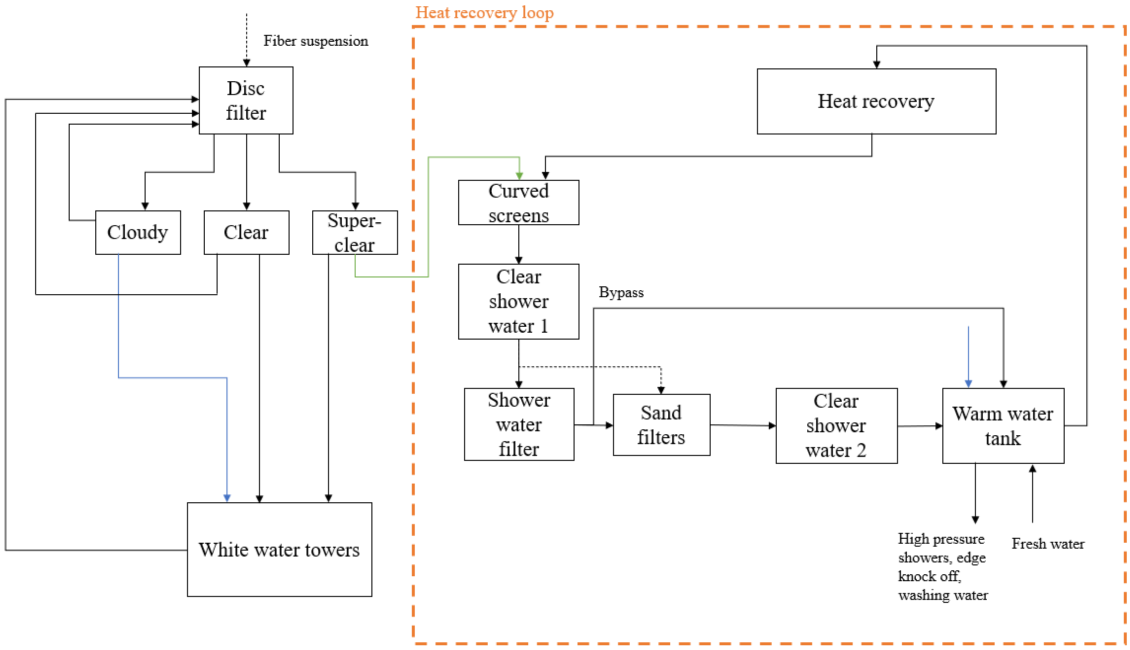

Figure 12 Main water loops in BM1. Green line represents the opportunity to optimize the water consumption by utilizing SCF in heat recovery loop. Shower water filter is not currently used in the process.

These loops differ from each other through end-uses of water and by quality of water. As described in Chapter 3, the SS content of white water is high and there are detrimental substances from the pulp. The water in heat recovery loop is throughout purer. The water is fresh water that is purified in fresh water treatment plant and circulated in the loop, and new fresh water is constantly introduced to the loop. (Marttinen, 2000) Currently, water in the heat recovery loop is purified with curved screens because the shower water filter is not in use. However, the shower water filter could be applied in use. The filtration grade of the curved screens is 500 µm and of the shower water filter 200 µm. The shower water filter is a pressure filter, and with the choice of filtration element the filtration grade of shower water filter can be reduced to 100 µm.

By applying SCF to the heat recovery loop the addition of fresh water could be decreased. Wastewater is mostly discharged as overflow from water towers or tanks. The amount of overflow could be decreased by removing SCF flow to white water towers and applying it to warm water tank where the fresh water is currently fed. This decreases the amount of wastewater, the fresh water consumption and the overall water consumption in board production. However, the possibility to utilize SCF to replace fresh water must be analyzed due to different water quality, as mentioned earlier. The analysis is further described in the following chapters.

EXPERIMENTAL PART

The experimental part of the thesis is divided into introducing the materials used in the experiments, the methods applied in the experiments, and to results and discussion. Last, the final conclusions are presented.

In the beginning of the experimental part the optimization of water use is carried out by analyzing the possibility of utilizing SCF more efficiently at BM1. The water consumption survey is followed by water quality analysis of SCF. In the second part of the experiments SCF is treated with membrane filtration to achieve the purity of pure shower water applied in the heat recovery loop. The analytical methods applied are TSS, COD, pH and conductivity. Filtrations took place at LUT University and other experiments at Imatra Mills.

The information in the experimental part is gathered from discussions with process operators and other employees, discussions with suppliers, P&IDs, process software and online laboratory measurements. Process software applied is Valmet DNA and Trimble Wedge. Other references applied are marked as usual.

6 MATERIALS

In this chapter materials used in the experiments are presented. Materials used can be divided into analyzed water and filter material. Water can be further divided into SCF and clear shower water and filter materials to filter cloths and membranes.

Water fraction under analysis in the experimental part is SCF from BM1 disc filter. Filtrate was collected from the sampling point multiple times during the experiments. By diversifying the sampling times the effect of different process conditions on filtrate quality could be observed. Samples were collected either in three one-liter container or in a five-liter canister. The equipment varied due to lack of similar sampling equipment. Also, all samples were analyzed within 24 hours from sample taking apart from few exceptions.

The quality of filtrate is compared to clear shower water. The shower water was collected few times from process line. Samples were taken from the line between the first shower water tank and a sand filtration unit. Sampling point was selected because there was a possibility to take the sample and the point is near the location where these water fractions could be combined. Also, taking the sample before sand filtration unit enables determining the quality of water before it is purified more in sand filtration.

Filter cloths used in the experiments are presented in Table VII. Filter cloths were used in microbial experiments and Sefar Nitex 41 was also used in filtration experiments.

Table VII Filter cloths used in the experiments (Sefar, 2007).

Filter cloth	Type	Material	Pore size, µm	Manufacturer
Sefar Nitex 15	Monofilament open mesh fabric	Polyamide	15	Sefar
Sefar Nitex 41	Monofilament open mesh fabrics	Polyamide	41	Sefar

Membranes used in the experiments are presented in Table VIII. In microbial experiments MV020, RC70PP and NF270 were used. The MF membrane (MV020) was only used in microbial experiments due to large pore size. Other membranes than MF were applied in filtration experiments.

Table VIII Membranes used in the experiments. References are marked as follows: (a) Microdyn-Nadir, 2020a, (b) Alfa Laval, 2021, (c) Microdyn-Nadir, 2020b, (d) Sterlitech, 2020a, (e) Snyder Filtration, 2021, (f) Sterlitech, 2020b.

Membrane	Type	Material	MWCO (g/mol, Da)	Manufacturer
MV020	MF	Polyvinylidene fluoride	0.2 µm (pore size)	Microdyn-Nadir[a]
RC70PP	UF	Polypropylene + regenerated cellulose acetate	10000	Alfa Laval[b]
UH004P	UF	Polyethersulfone	4000	Microdyn-Nadir[c]
NF270	NF	Polyamide thin-film composite	200-400	Dow FilmTech[d]
NFX	NF	Polyamide thin-film composite	150-300	Snyder Filtration[e]
BW30	RO	Polyamide thin-film composite	~100	Dow FilmTech[f]

7 METHODS

In this chapter methods for water consumption determination and optimization are reviewed. Also, analytical methods applied are presented. First, the execution of water consumption survey is described. Then, the possibilities for optimization that are divided into determination of water quality and the effect of filtration on the water quality are addressed. Last, the determination of microbial activity of filtrate is presented.

7.1 Determination of water consumption in BM1

The water consumption survey was carried out by collecting data from process software called Wedge. Data was collected every minute from years 2018, 2019 and 2020. Data was first screened in Wedge but mostly analyzed in excel. Data was screened for errors and missing data points and these points were deleted to enable the data analysis. In 2020 there were a two-week union strike that affected the production of BM1 by increasing downtime. The effect of the strike is neglected in this survey.

The main flows under analysis are incoming flows to the process and discharge flows in order to determine the water consumption. The focus is on fresh water which covers raw and chemically treated water presented in Figure 11. Water transporting with the stock is left out of analysis because it is fiber suspension rather than pure water fraction. Also, cooling water, sealing water and steam are left out of analysis because the focus is on water used directly in production process.

As mentioned earlier, by utilizing SCF in the heat recovery loop instead of white water loop water consumption could be decreased. The amount of SCF that forms at the disc filter was determined by comparing dimensioning of disc filter to current flows. Data used in the analysis were collected in 2020. In the calculations it was assumed that by redirecting SCF to the heat recovery loop, overflow of water towers could be decreased the same amount that SCF is formed. It is based on the fact that excess water is removed constantly from the white water loop. Simultaneously, fresh water is added to the heat recovery loop which would also be decreased. The survey was executed by help of a supplier that has designed the filter in question.

7.2 Execution of the filtration experiments

Filtration was applied to purify the SCF. The purpose of filtration experiments was to achieve the purity of clear shower water. Different membranes and one filter cloth were applied in order to determine the required degree of purification.

Amicon Millipore filtration unit was used in filtration experiments. The unit represents dead-end membrane filtration discussed in the literature part of the thesis. The filtration set-up is presented in Figure 13. Data from membrane filtrations was collected using application called Massflux that collected weight of permeate as function of time.

Figure 13 Amicon Millipore filtration unit used in the experiments. The filtration unit is in the middle on top of heating plate with magnetic stirrer. Pressure was adjusted with valve on the left and scale used in the weighing is on the right. Temperature was adjusted with a digital thermometer.

Membranes were pressurized before filtration by applying high pressure on membrane for 20 minutes. Before the pressurization RC70PP, NFX and BW30 were soaked in deionized water for 5 to 12 hours to wet the membrane before filtration. To observe the effect filtration has on membrane fouling pure water permeability was measured for each membrane at 25 °C before and after filtration.

The membranes used in filtration experiments and the pressures applied in each filtration are presented in Table IX. The volume of feed was 300 ml and the temperature 50 °C in every experiment.

Table IX Pressures applied in filtrations. The volume of feed was 300 ml and the temperature 50 °C with every membrane.

Membrane	Pressure, bar
RC70PP	2
UH004P	5.5
NF270	4
NFX	5.5
BW30	5.5

One exception in filtration experiments was the filtration with a filter cloth of 41 µm. The volume of feed was 1000 ml, and the filtration was performed by refilling the filtration unit of 300 ml and collecting all permeate to a container. Filtration was performed by this way in order to achieve enough permeate to be able to measure the SS concentration reliably.

7.3 Determination of microbiological activity of SCF

Microbiological tests were carried out to determine the microbiological activity of SCF and the effect filtration has on it. Two samples were collected, and samples were collected within one day. The first sample was collected in the morning and the second one 10 hours later. Sample volumes were five liters. Samples were transported to LUT University where the experiments were conducted. The samples from the experiments were transported back to board mill and the microbial tests were started within 24 hours from the sampling. Microbial experiments were carried out by Stora Enso personnel. Colony forming unit was measured according to internal instructions of Stora Enso for CFU measurements. Measurements were conducted in 32 °C in agar nutrient solution. Three parallel colony forming unit experiments were done from each sample.

Filtration experiments were completed in order to determine how effectively microbes are removed by filtration and to determine the effect filtration has on microbial activity. Three membranes and two filter cloths were applied in the experiments. Filter cloths were Sefar Nitex 15 and Sefar Nitex 41 and membranes MV020, RC70PP and NF270. Experiments were executed in two sets because the time limit of analyzing samples were strict. In the first set nano- and ultrafiltration membranes and filter cloth with pore size of 15 µm were applied. In the second set microfiltration membrane and filter cloth with pore size of 41 µm were applied. Membrane performance in filtration was not under analysis in these experiments. A control sample was determined to measure the effect the experimental conditions had on CFU of the filtrate. The control sample was kept in the fume hood, where the experiments were performed, for three hours to investigate if the fume hood affects the CFU.

7.4 Analytical methods

Fiber size of SCF was determined with Valmet Fiber Image Analyzer (FS5). Parameters under analysis were fiber length and width and fines in the sample. The sample volume was one liter. The analysis was conducted by Stora Enso personnel at Stora Enso Imatra Mills. The analysis of fiber length and width can be applied in determination of separation efficiency of filtration. (Valmet, 2021b)

In order to determine the quality of SCF, TSS, COD, pH and conductivity were measured. Three parallel SS measurements were done from every sample to increase the reliability of the results. Samples were stored at room temperature and were analyzed within 2 to 24 hours of sample taking. The storing was carried out at room temperature because it was not considered to impact the results significantly and the forming of precipitates wanted to be avoided. Because some of the experiments were conducted at LUT University and some at Stora Enso laboratory, analyses were conducted in both laboratories. The main analysis methods are the same but there are differences depending on available equipment. First, the analytical methods at Stora Enso are described.

TSS was measured using vacuum filtration and Macherey-Nagel 640m filter paper with retention of 4 - 12 µm. The filtration paper was prepared by drying to standard weight in an oven for 1 hour and weighed with 0.1 mg accuracy after cooling in a desiccator for 20 minutes. The filtration was carried out by filtrating an exact volume of the sample after which the sample and the filter paper was dried in an oven at 105 °C for 2 hours. According to SFS-EN 872 (2005) the sample volume should be selected so that the dry residue on the filter paper is at least 2 mg, but preferably between 5 to 50 mg, and exceeding the volume of 1 l should be avoided. Thus, the sample volume varied between 600-900 ml being 800 ml in most experiments. Samples that did not exceed the limit of dry residue of at least 2 mg on the filter paper were deleted except for one sample where all the three parallel measurements were under 2 mg. A one-liter measuring glass was applied in the measurements, and the volume was measured with 10 ml accuracy which is within the requirements of the standard SFS-EN 827 (2005). The paper was cooled in a desiccator for 15 to 20 minutes and then weighed again with 0.1 mg accuracy. The scale used in weighing was Mettler Toledo AX204.

COD was measured using Nanocolor COD 15 - 160 mg/l and 100 - 5000 mg/l test tubes. 2 ml of sample was pipetted with Biohit Proline 100 - 5000 µl pipette to COD test tube and the tube was shaken and then put to water bath with temperature control of 148 °C for 2 hours. The tubes were cooled and then measured with Nanocolor 500 D spectrophotometer that measured the COD concentration in the tube. COD in some samples exceeded the 160 mg/l limit but the samples were not diluted. These samples were not included to the results. Conductivity was measured using Valmet Kemotron conductivity meter. pH was measured using Mettler Toledo pH meter.

The performance of filtrations conducted at LUT University was measured with same parameters as the quality of filtrate that are COD, pH and conductivity. SS was measured only from the feed before filtration and from the permeate of filtration with filter cloth. The analyses were carried out the same way as the ones at Stora Enso. However, filtration paper used in the measurements was Whatman 1442-070 filter paper with retention of 2.5 µm. COD was measured using Merck COD Cell Test. 2 ml of sample was pipetted with Sartorius Picus 100 - 5000 µl pipette. The range of COD tubes was 0 - 150 mg/l so the sample from the feed and filter cloth permeate were diluted with a dilution function of the pipette. Results were measured with Hach DR/2010 spectrophotometer. pH was measured using 744 pH Meter by Metrohm and conductivity by using Conductivity Meter 703 by Knick.

7.5 Calculations

Specific water consumption (SWC) can be determined with Equation (1) from process data of wastewater flow and production rate.

$$Q = \frac{\dot{V}}{R} \tag{1}$$

where $\dot{V}$ volumetric flow of wastewater, m^3/h

R production of BM1, t/h.

The effect of applying SCF to the heat recovery loop to SWC can be evaluated with Equation (2) where Q_1 is calculated with Equation (1).

$$Q_2 = Q_1 - Q_{SCF} \tag{2}$$

where Q_{SCF} generation of SCF, m^3/t_{board}.

The generation of SCF can be determined with Equation (3) when feed to disc filter is known. In this case *k* is 0.19 according to P&ID.

$$Q_{SCF} = \frac{k\dot{F}}{R} \tag{3}$$

where k percentage of SCF from disc filter feed, %

$\dot{F}$ volumetric flow to disc filter, m^3/h.

TSS concentration can be calculated from the results with Equation (4).

$$TSS = \frac{m_1 - m_2}{V_1} \cdot 1000 \tag{4}$$

where m_1 mass of filter paper, mg

m_2 mass of filter paper and sample, mg

V_1 volume of sample in filtration, ml.

Filtration mass flux can be calculated from collected data with Equation (5) according to Mulder (1996). Filtration area applied is 38 cm^2 in all filtrations.

$$J = \frac{m_{\mathrm{p}}}{At} \tag{5}$$

where m_{p} mass of permeate, kg

A filtration area, m^2

t time, h.

According to Mulder (1996) permeability can be calculated from the filtration flux with filtration pressure as presented in Equation (6).

$$P = \frac{J}{p} \tag{6}$$

where p pressure applied in filtration, bar.

Retention of SS, COD and conductivity can be calculated with Equation (7) according to Mulder (1996).

$$R = \frac{C^{Feed} - C^{Permeate}}{C^{Feed}} \tag{7}$$

where C^{Feed} concentration of observed parameter in the feed

$C^{Permeate}$ concentration of observed parameter in the permeate.

8 RESULTS AND DISCUSSION

Finally, the results of experimental part are presented and discussed in this chapter. First, water consumption survey is addressed followed by the water quality analysis of SCF. Then, effect of filtration on water quality is determined and lastly, possibilities for error in the experiments are being discussed. The results are presented as percentages to avoid the exposure of confidential information.

8.1 Water consumption of BM1

The specific water consumption (SWC) of BM1 was determined with Equation (1) for years 2018, 2019 and 2020 and the results are presented in Figure 14 compared to reference year of 2018. The SWC is presented for the whole year containing both downtime and production. January in 2018 is left out of analysis due to lack of data but it is not considered to have a significant effect on the yearly water consumption. The values are determined from discharged wastewater as m^3_{water}/t_{board}. Additionally, the monthly minimum and maximum values of SWC were determined for each year. The extreme values are presented similarly as the SWC that is compared to the reference value of year 2018. In 2018 the range of SWC is from 72 % to 109 %, in 2019 from 65 % to 133 % and in 2020 from 36 % to 110 %. So, in 2020 water consumption varied the most because the range of the monthly extreme values is the largest. The reasons for this are further discussed within the next figure but, from this figure it can be observed that water consumption in 2020 was lower than in the two previous years.

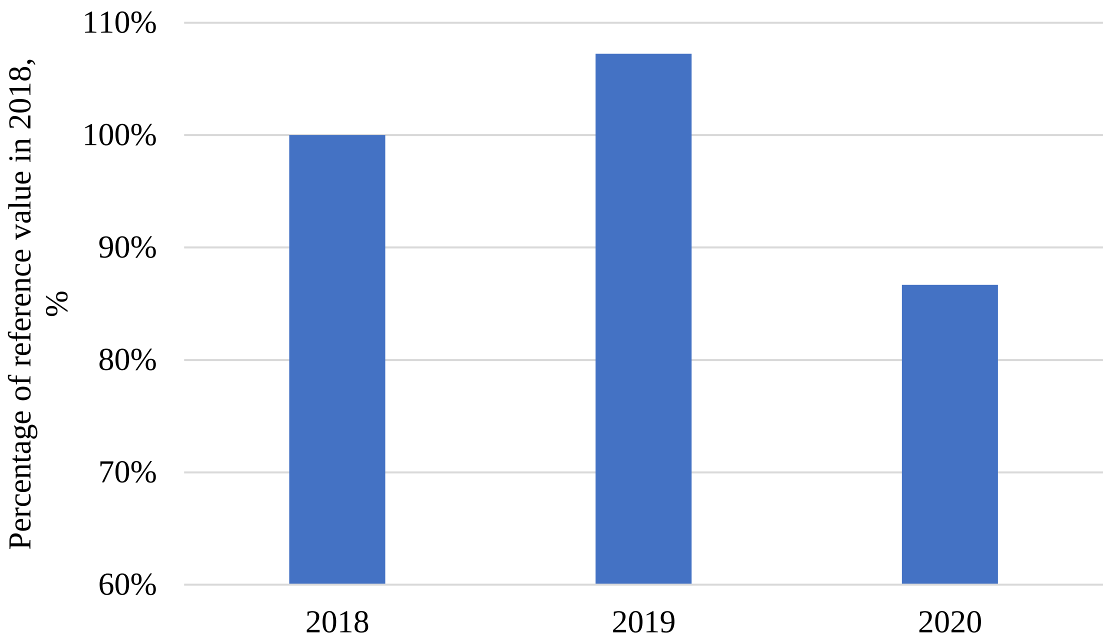

Figure 14 Specific water consumption of BM1 in 2018, 2019 and 2020 compared to the SWC in 2018.

The fresh water consumption during downtime is presented in Figure 15 for years 2018, 2019 and 2020. The values are presented as percentage of the fresh water consumption in 2018 which is the selected reference year. January in 2018 is left out of analysis due to lack of data but it is not considered to have a significant effect on the water consumption. As can be observed the consumption of raw water is nearly the same in all three years. However, the consumption of chemically treated water is significantly lower in 2020 comparing to 2019 and 2018. The lower chemically treated water consumption is mostly due to downtime in BM1. Chemically treated water is applied in targets such as warm water in high pressure showers and chemical dilutions. During downtime the requirement for water in these applications is minor.

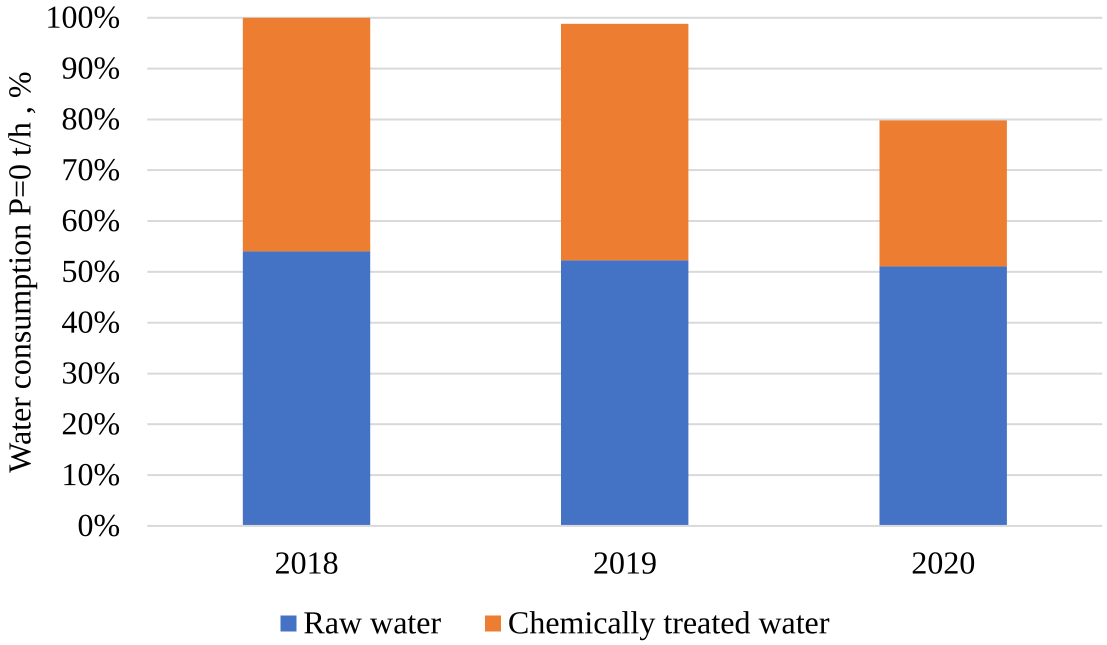

Figure 15 The yearly average fresh water consumption when production is 0 t/h as percentage of the fresh water consumption in 2018.

In addition, the nature of downtime affects the water consumption. In 2020 there were more longer downtime situations, when in 2019 and 2018 the situations were more scattered. Many short breaks of production lead to higher water consumption than few longer ones. In a short break, where the intention is to continue production immediately, water has to be continuously added to the process in order to ensure the water sufficiency. In longer downtime situations, like for days, the water intake is lower than in shorter ones because the water intake is abstained for a longer time period which enables to decrease the water consumption near or completely to zero.

The effect of applying SCF to heat recovery loop on SWC was estimated based on determined water consumption and generation of filtrate. The generation of SCF per ton of produced board was determined based on the P&ID and process data. From P&ID it was determined that SCF formation is 19 % of the feed to the disc filter. The actual generation of SCF was calculated with Equation (3) for average values of $\dot{F}$ and R in 2020. The obtained value was used to estimate the reduction of water consumption by applying SCF to heat recovery loop with Equation (2). It was assumed that half of the generated SCF could be applied in the loop. The assumption was done based on the amount of water that circulates in the heat recovery loop and the additional water applied in the loop. Half of the generated SCF comprehends 34 % of the water in the loop. Based on the average SWC in 2020, SWC could be reduced by 30 % by utilizing half of the generated SCF. So, with further investigation, the amount of SCF could be increased if the exact value of the additional water is determined and the quality changes caused by the change of water does not affect the production process. With higher amount of SCF the concentrations of compounds become higher in the loop when there is not enough fresh water to dilute the water in the loop. So, in theory it could be possible to apply all the SCF to the heat recovery loop an reduce SWC even more but, in practice, it requires more investigation and trial runs.

8.2 Quality of SCF and factors affecting the quality

The quality of SCF is examined through fiber length distribution of SCF, SS, conductivity, COD and microbial activity. Also, the quality during downtime is addressed to determine the effect downtime has on the filtrate.

8.2.1 Fiber length

Fiber length distribution of SCF is presented in Figure 16. The average fiber length is 532 µm and width 12.4 µm. As can be seen in Figure 16, most of the fibers belong to the first and the third fractions that consists of fibers with length of 0 to 200 µm and from 600 to 1200 µm with percentages of 40.5 % and 36.6 %. Rest of the fibers belong to second and fourth fractions with fiber lengths of 200 to 600 µm and 1200 to 2000 µm with percentages of 14.4 % and 8.3 %. There were no fibers over 2000 µm in the sample. The fines in SCF can be divided into flake-like fines and lamella-shaped fines. The percentage of flake-like fines that are classified as particles shorter than 200 µm was 43 % of the projection area of all measured particles. The percentage of lamella-shaped fines that are particles with width less than 10 µm and length over 200 µm was 1.8 % of all measured particles longer than 200 µm.

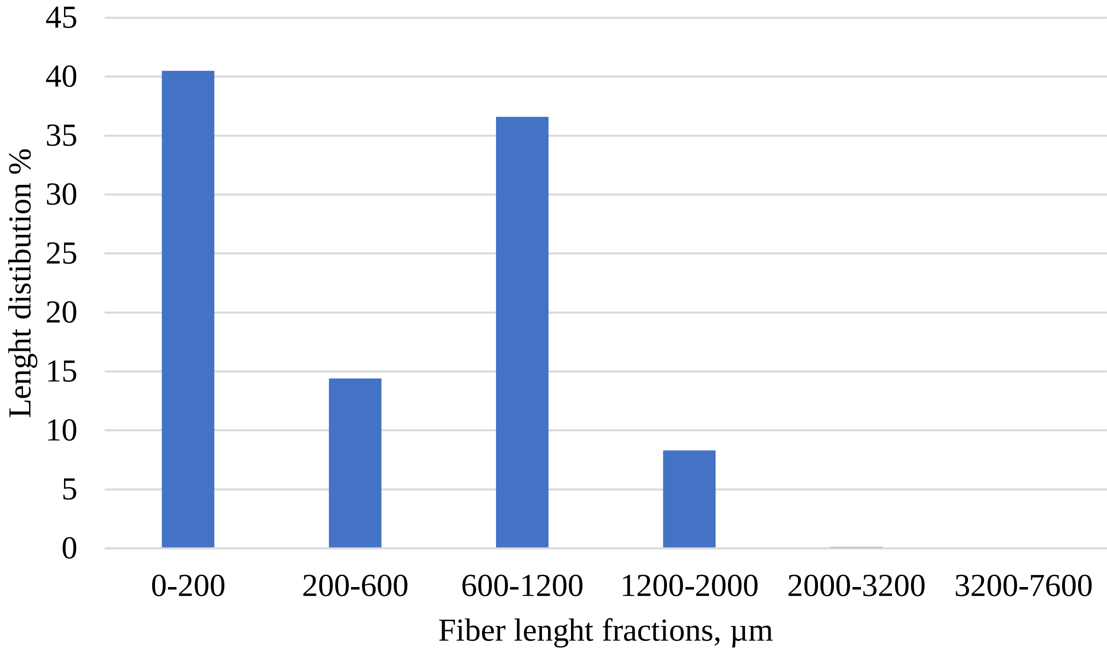

Figure 16 Fiber length distribution. The average fiber width is 12.4 µm.

When considering the average fiber length and fiber length distribution the curved screen with separation of 500 µm is not efficient in removing fibers in SCF. The shower water filter with separation of 200 µm could remove some of the fibers. However, the fiber width is only 12.4 µm which enables even the longest fibers passing through the filter when entering the filter in a right angle. The fines in SCF are small as described earlier which means that fines most likely pass through the shower water filter.

8.2.2 SS

The SS concentrations of 20 samples analyzed are presented as histogram in Figure 17. The marking [x -y] means that all the values between the set limits are included including the x and y values, and the marking]z - w] means that z is not included to the set but w is. As can be observed, the SS of SCF is generally from 2 to 6 mg/l, the average value being 5 mg/l with deviation of 2.7. There was no turbidity observed visually in the sample. Small particles could be observed after shaking the sample, but the overall appearance was clear. Samples taken during production are included in this figure, but the production time is not considered. The average pH of all samples was 4.4 with deviation of 0.08.

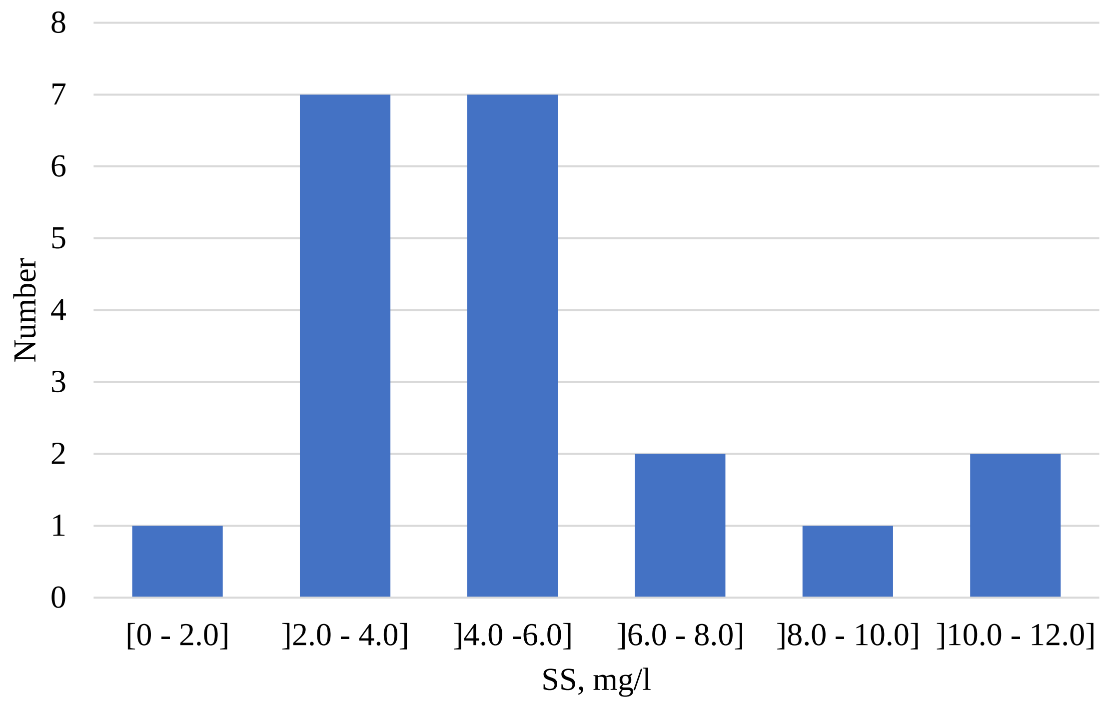

Figure 17 Histogram of SS concentration of SCF in the collected samples. The marking [x -y] means that all the values between the set limits are included including also the x and y values, and the marking]z - w] means that z is not included to the set but w is.

The SS in SCF during the sampling period can be compared to SS of the whole year that is presented in Figure 18. It can be seen, that the most of the measured values settle to under 10 mg/l and, to be more exact, from 1 to 4 mg/l. The average SS is 6 mg/l with deviation of 7.2. The reasons for the variation of SS in SCF is adduced more deeply in Chapter 8.2.2. As can be concluded from the number of measurements in Figure 18, SS is not measured daily but according to a measurement plan that is not further described here.

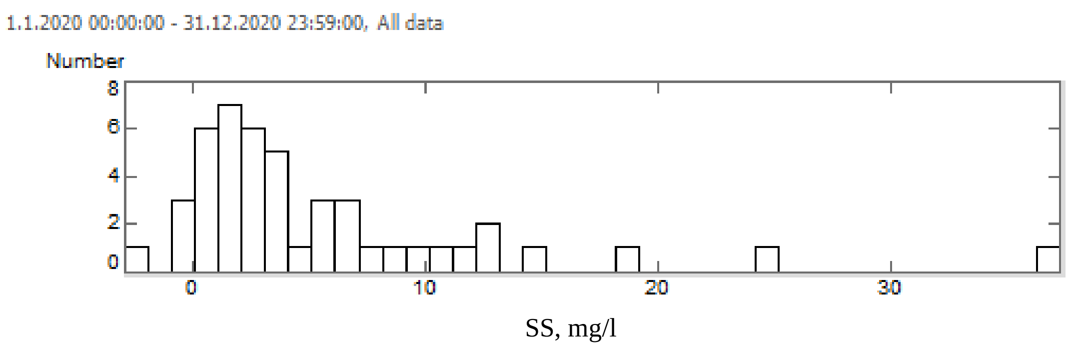

Figure 18 Histogram of SS of SCF from entire year of 2020. Data is collected from process software called Wedge, and it is based on laboratory measurement results.

To determine the effect of the production time on filtrate quality, a few samples are taken into closer observation. In the next three figures these samples are compared through SS (Figure 19), conductivity (Figure 23) and COD (Figure 24). The samples are divided into three series by the sampling. So, the samples from each series are taken from the same BM1 production period. The samples of the first series are taken after board machine start-up situation to monitor the quality changes of the SCF. So, the first sample is taken after one hour of continuous production and the seventh sample after 45 hours of production. The grammage changed after 27 hours and the last two samples are of other grammage than the first five samples. The other samples are taken in between at times presented. The samples of the second series are taken after 41 to 48 hours of production and are not related to the first series. The samples of the third series are from another start-up situation from 1 to 8 hours. Each figure is further addressed below.

As can be seen in the Figure 19, the sample from the first series taken one hour after a start-up contains highest amount of solids. In the first series the concentration decreases as function of time. In the second series SS do not decrease as function of time but there is a little variation in the measured values. In the third series the SS in the first sample is much lower than in the one of the first series and the concentration decreases through time. The variation between the sets supports the conclusion that the quality of SCF is also affected by other factors than the duration of board production. In addition, the second series proves that SS concentration does not necessarily decrease as function of BM1 production time. There is a clear connection with SS in SCF and BM1 production, but the concentration varies depending on broke consistency, feed and rotation speed of filter. Unstable conditions might cause a bad formation of fiber mat which leads to solids passing through the filter. Changes in feed consistency and feed amount effect the rotation speed of filter which effects the quality of filtrates as described in Chapter 4.1.2. For instance, when broke feed decreases, the amount of fiber suspension in the disc filter lowers which makes the rotation speed to decrease. In addition, more sweetener, that is thickened pulp, has to be fed to filter in order to enable the formation of the fiber mat to the discs’ surface to ensure the solids removal. These factors affecting SCF quality in each series are being discussed in detail below.

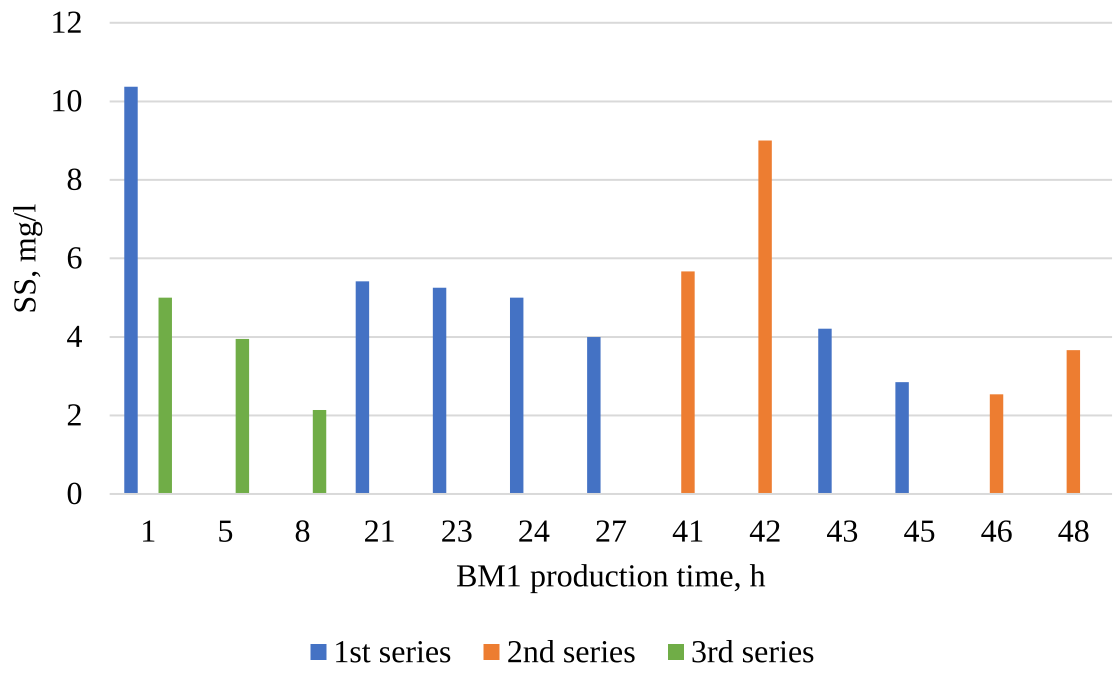

Figure 19 SS of SCF as function of BM1 production time. Three separate series are being examined.

In the first series the consistency of broke was high in the first sample due to tale threading of BM1 which is a part of machine operation but is not considered as normal process condition. Generally, in tale threading broke is formed more than in stable process, and the formed broke is transported to the broke tower from where it is fed to the filter. The higher formation of broke is caused because the forming web is led to pulpers in tale threading before the web reaches the reeler. Disc filter must adjust the changes in consistency and of flowrate that are caused by higher formation of broke. It destabilizes the disc filter operation and might increase the solids passing to the filtrates.

The main factors affecting the SCF quality are presented in Figure 20 from the sampling period. The difference between broke feed and the overall feed to the filter is that the broke feed comprehends only the flow from the broke tower and the overall feed contains also sweetener, white water and cloudy filtrate that is recycled back to filter. As can be observed from the Figure 20, the overall feed to disc filter remains quite constant proceeding the series with no large variations but the broke feed varies which increases the consistency of the feed momentarily. However, no large consistency variations happened during the sampling which makes the filter operation stable and solids removal efficient. In the second to last sample the broke consistency had dropped and the vacuum in the drop leg is quite low. In the last sampling the broke feed and consistency increases and simultaneously the vacuum in the drop leg increases. This indicates that better fiber mat is formed at the disc's surface. The results support these observations because the SS is lower in the last sample compared to the one before. The vacuum in the drop leg effects on the distribution of filtrates and to the quality of filtrates. As described in Chapter 4.1.2, the vacuum improves the formation of the fiber mat. A slight effect of pressure difference to SS can be observed in the first series of Figure 19. When the pressure difference of different sampling times was compared to SS, it can be observed that with higher pressure differences SS is lower. However, the correlation does not apply to all of the samples and thus, should be investigated more deeply in order to make steady conclusions. It can, however, be observed that the vacuum increases when the broke feed increases. In the first and second series the vacuum is higher when the broke feed increases. The observation applies both on peak flows in the first series and on more sedate rise of broke feed in the second series. In the third series, the broke feed remains quite stable as does the vacuum.

Another factor affecting the broke amount is the winder and more specifically the edge trimmings. The broke amount coming from the winder is depended on trimmings that are cut off at the winder. With wider trimmings more broke is generated at the winder than when trimmings narrower. So, wide trimmings of winder can increase the broke feed and broke consistency to the disc filter. During the first series the trimmings were wider during the last sampling than during the second last sampling. As can be observed from Figure 20, the broke feed is higher in the last sampling than the one before which is probably due to the wider trimmings. Additionally, besides broke from winder also broke pulping affects the broke feed. However, according to Figure 19 SS is lower in the last sample which proves that higher broke feed does not necessarily increase the solids passing to the filtrate but can also impact on the formation of the fiber mat that retain the solids on the disc filter surface.

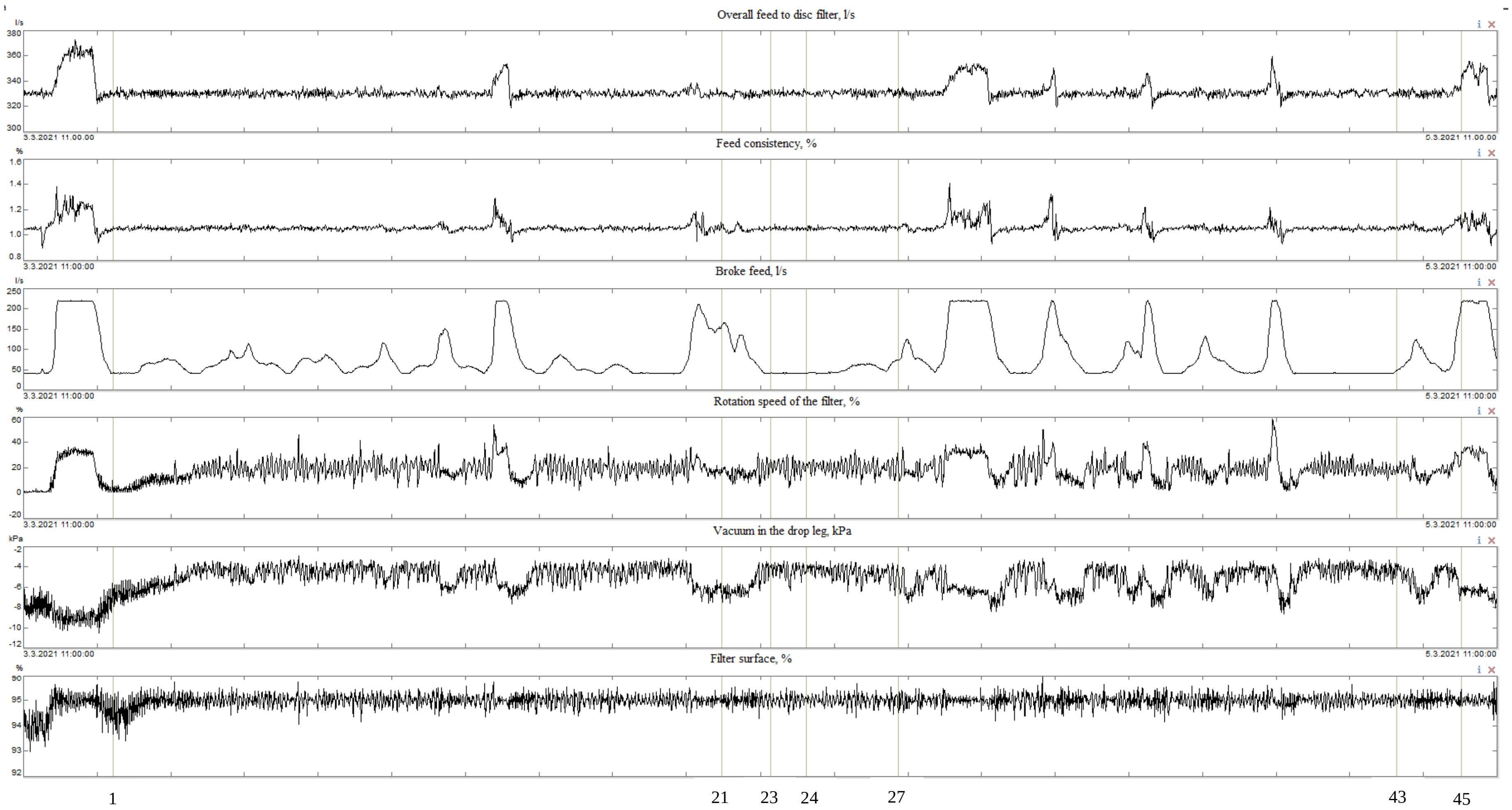

Figure 20 Factors affecting the SS concentration in the first series. The sampling period under observation is from March 3rd at 11 am to March 5th at 11 am, and the samplings are marked with vertical lines. Datasets from top to bottom are overall feed to disc filter, consistency of feed, broke feed, rotation speed of the filter, vacuum in the drop leg of SCF and filter surface.

The factors affecting the quality of SCF for the second series are presented in Figure 21. In the second series the high amount of SS in the filtrate is due to changes in filter surface that mean changes in the amount of fiber suspension in the vat. Too low a suspension surface causes the filter speed to increase, increases the solids in the filtrates and lowers the capacity of the filter. Also, the solid content of fiber cake is lower which means that the fiber cake is not dewatered efficiently, and there might be issues with detaching the cake. The cleaning sequence of the disc filter does not change depending on the rotation speed of the filter. This may lead to clogging of filter cloth if the rotation speed of the filter is high for long. The capacity of the filter decreases if the filter cloth gets clogged.

As can be seen in Figure 21, the variation of filter surface has been higher before the second and the last sample that are taken after 42 and 48 hours of production than before the other two samples. In these samples SS concentration was higher than in the other two samples. The variation is much lower in the other two samples that have lower SS concentration. It can be observed that an increase of broke feed to the filter, increases the filter surface variation. Increased broke feed is caused by rise of couch pit surface that rises when broke is pumped to it from the pulpers. So, the broke that is pulped at the machine to ensure the broke sufficiency during stable production and the broke coming from the winder impact the filtrate quality. Hence, the broke pulping should be kept stable to avoid flowrate and consistency peaks, and with that, the solids passing to the filtrates.

The effect of wide trimmings of winder can be detected in the second series. The trimmings were wider during the second sampling than during the first which can be detected in Figure 21 as increased broke feed. There was no operation at the winder during the third sampling which means that no broke is formed at the winder which can be detected in the low broke feed to filter. During the last sampling the trimmings were wide and the solids concentration in the filtrate was higher than in the one before.

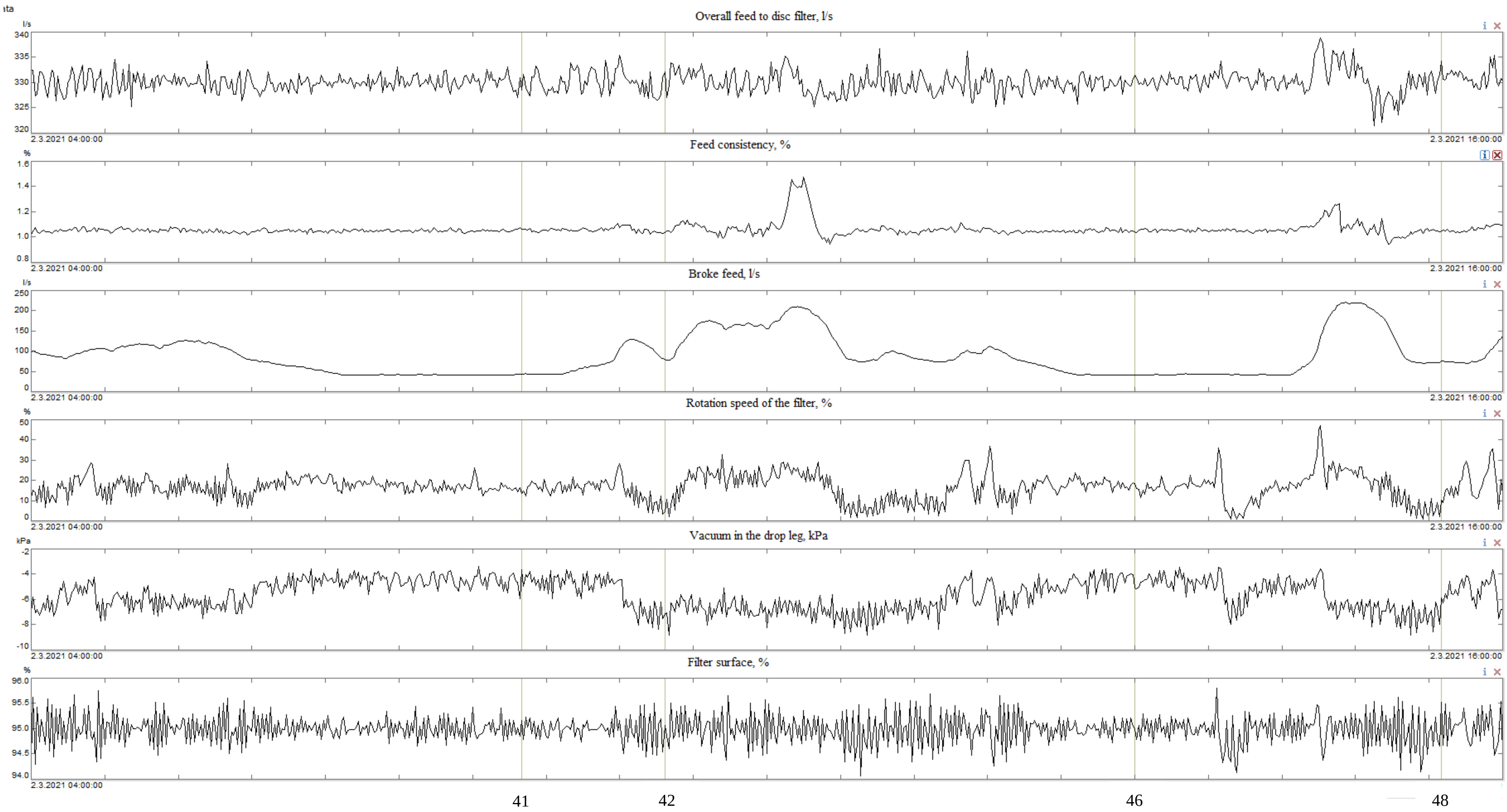

Figure 21 Factors affecting the SS concentration in the second series. The sampling period under observation is from March 2nd at 4 am to March 2nd at 4 pm, and the samplings are marked with vertical lines. Datasets from top to bottom are overall feed to disc filter, consistency of feed, broke feed, rotation speed of the filter, vacuum in the drop leg of SCF and filter surface.

The factors affecting the quality of SCF for the third series are presented in Figure 22. On contrary to other series, the consistency of broke feed is below 0.5 % during the first sampling. During the tale threading the amount of broke in the broke tower has increased considerably which led to higher feed of broke to the filter. However, as can be seen from Figure 22, the broke consistency and broke feed start to decrease simultaneously. This causes the rotation speed of the filter to increase considerably as the consistency changes. The reason for consistency to decrease so rigidly is that there was no sweetener flow to the disc filter until the point where the filter surface stabilizes. With low broke feed and lack of sweetener, the consistency drops. The reason for the missing sweetener is not known but it is possible that it is due to malfunction of equipment, for instance.

From this series the effect of consistency and broke feed to filter operation can be easily observed via changes of all the factors after the first sampling. Changes in the feed affect the suspension surface in the vat which makes the rotation speed to vary. During the last two samplings of the third series, the operation of the filter is stable on contrary to the other two series presented above. There are no flow or consistency peaks, and the vacuum remains high. The trimmings of the winder remained the same during this series. The rotation speed of the filter was a little bit lower during the second sampling compared to the third which may have affected the solids concentration in the filtrate.

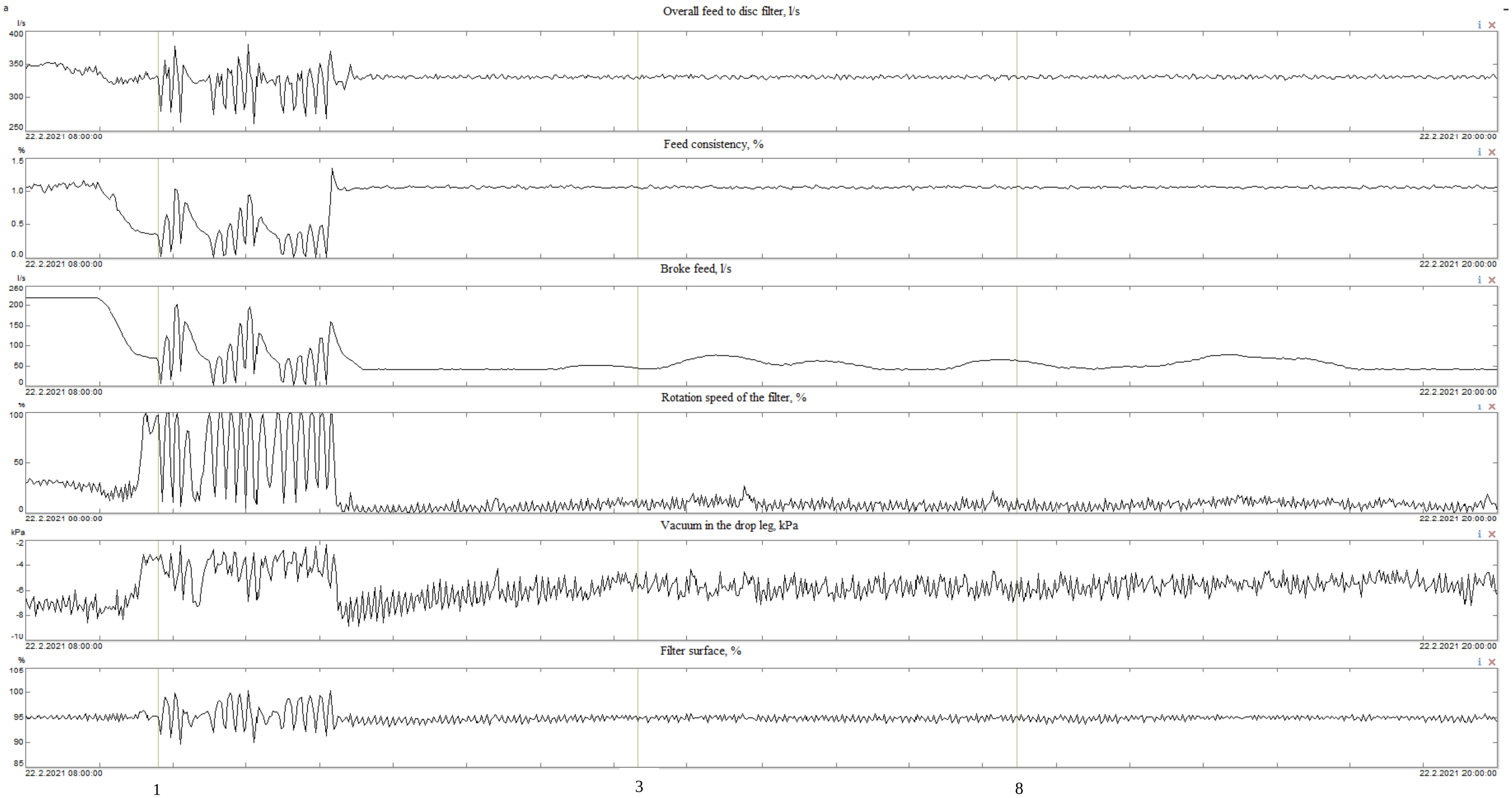

Figure 22 Factors affecting the SS concentration in the third series. The sampling period under observation is from February 22nd at 8 am to February 22nd at 8 pm, and the samplings are marked with vertical lines. Datasets from top to bottom are overall feed to disc filter, consistency of feed, broke feed, rotation speed of the filter, vacuum in the drop leg of SCF and filter surface.

In conclusion, SS in the filtrate is affected most by fiber suspension surface in the filter vat and broke feed that affects the consistency. Changes in the filter surface level accelerate or slow down the rotation speed of filter that affects the filter capacity and performance. Broke feed peaks destabilize the filter operation by increasing the rotation but also the vacuum that enhances the formation of the fiber mat. Although sweetener, that is almost constantly fed to filter, is cut off during broke feed peaks, with high flowrates of broke the consistency of feed increases. The effect on broke peaks cannot be fully determined due to lack of data on those moments but according to the second series, SS is higher in the samples taken after broke feed peak, 9.0 mg/l and 3.7 mg/l, than in the ones taken before, 5.6 mg/l and 2.5 mg/l.

8.2.3 Conductivity and COD

Conductivity of each sample is presented in Figure 23. As can be seen, conductivity is at its lowest in the first samples of the first and third series and rises with the rest of the samples in each series as production proceeds. Additional water reduces the conductivity by diluting the water, and chemical dosing increases the concentrations and thereby conductivity. The requirement for additional water is higher during web breakage and start-up situations. New water is applied in the process which dilutes the circulation waters and lowers the concentrations of salts. When in stable production compounds accumulate in the circulating water which can be observed with higher conductivity, for instance. All in all, conductivity of SCF remain quite constant and varies between 51 to 60 mS/m in stable production. The average conductivity of all measured samples was 56 mS/m with deviation of 4.4.

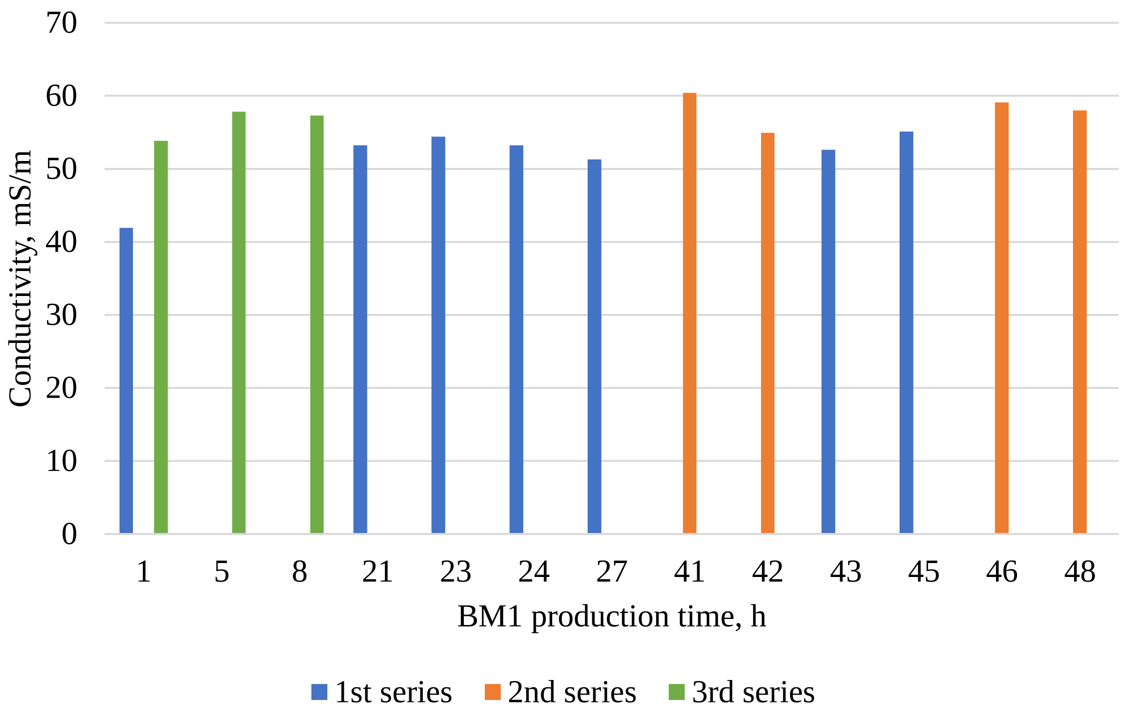

Figure 23 Conductivity of SCF as function of BM1 production time.

Changes in COD as function of BM1 production time are presented in Figure 24. COD is presented only for the first and the second series because it was not measured from the third series. The average COD was 220 mg/l with deviation of 61.2. Also, the median of COD was 220 mg/l. In the first series, COD decreases from 21 to 24 hours after which it remains in the same level in the fifth sample. The sample taken from 43 hours of production has considerably lower COD than other samples in the series. In the last sample COD is higher than in the sample before. When comparing COD to SS of these samples, a connection can be observed. As SS decreases in Figure 19 from 5 to 4 mg/l in 21 to 27 hours, also COD decreases from 318 mg/l to 209 mg/l in Figure 24. However, the observation does not apply for the rest of the samples, but they behave rather the opposite. When comparing the COD with Figure 20, it can be observed that COD is higher in the samples taken while broke feed and consistency is high. So, COD is higher in samples taken from 21 and 45 hours of production than the rest of the samples. The low COD of the sample 43 might be due to long and stable broke feed to the filter.

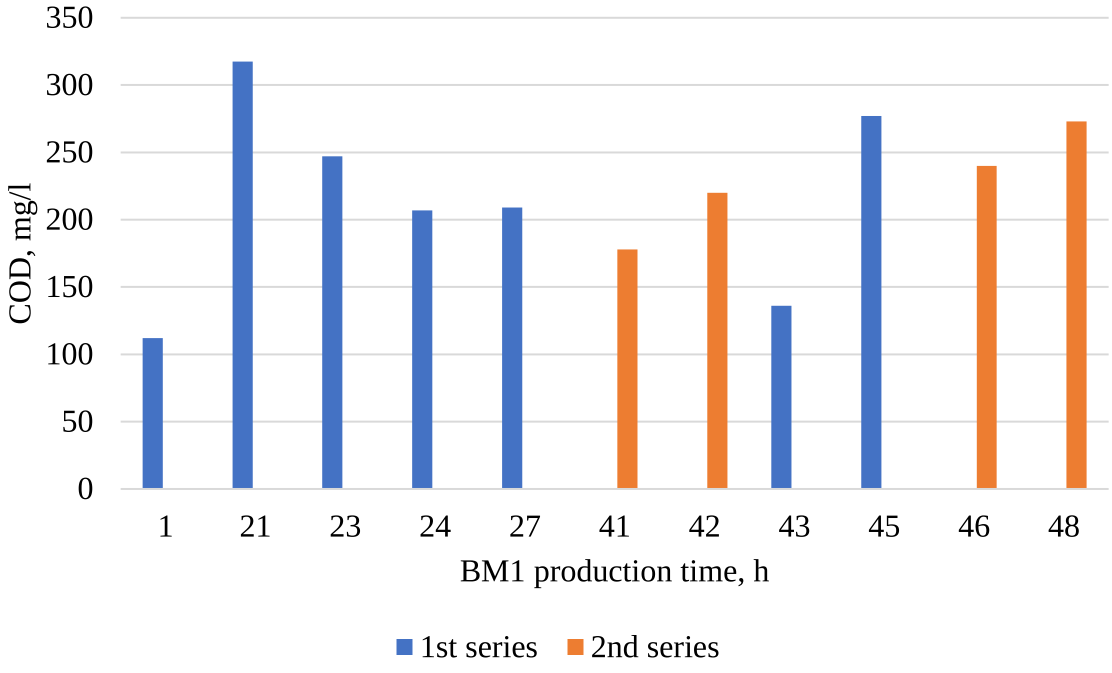

Figure 24 COD of SCF as function of BM1 production time.

In the second series COD rises from 178 of 41 hours to 273 mg/l of 48 hours. When comparing Figure 24 and Figure 19, COD correlates to SS by being lower with lower SS and higher with higher SS. However, on contrary to SS concentrations that are lower in samples 46 and 48 than in 41 and 42, COD is higher in samples 46 and 48 than in 41 and 42. There is no clear explanation for this found in the data, but the difference might be due to slightly higher overall feed to disc filter in the last two samples. Additionally, longer production time increases the water circulation which increases the concentrations. The quality of pulp and CTMP might vary which impacts the components transporting with the stock and might increase the COD in filtrates.

8.2.4 Quality during disturbance

The quality of SCF was measured from the samples collected during disturbance at BM1. Altogether four samples were collected of which three was from the same web breakage. In addition, the three samples were collected right before the first series discussed in Figure 19, Figure 23 and Figure 24. From the three samples the first one was collected when 30 minutes of tale threading was passed. The second one was collected a half hour after that and the third one a few minutes later when the tale threading was finished. The fourth sample was collected from another tale threading situation when 20 minutes had passed, and the production was started.

The measured parameters from the samples are presented in Table X. It can be observed that COD and conductivity of the first three samples, that are from the same disturbance, are considerably lower than during a stable production. As learned earlier, the average COD during stable production is 220 mg/l while in the three samples it is from 111 to 125 mg/l. The same applies for conductivity which is nearly a half of the value during stable production. The quality of the fourth sample differs from the others with all the parameters being higher.

Table X SCF quality during tale threading. Samples 1, 2 and 3 are from a same tale threading event sampled at different times. The sample 4 is from another tale threading.

Sample	SS, mg/l	COD, mg/l	pH	Conductivity, mS/m
1	7	125	4.4	30.5
2	4	111	4.5	32.2
3	5	111	4.5	33.0
4	9	216	4.3	53.6

The main difference between the two disturbances in question is the duration of downtime. The first disturbance lasted nearly three-times as long as the second one. Longer disturbance leads to higher amount of additional water in the process which dilutes the circulation waters which can be observed in Table X in COD and conductivity. When the fourth sample was taken the chemicals dosing to the stock was not yet started. However, the dosing is not considered to affect the measured quality significantly because the duration of downtime is more major factor. But the chemicals dosing can affect to compounds sticking to the web which could explain the higher concentrations in the sample. SS is higher than in stable production as was assumed. SS is affected by broke consistency and the amount fed to disc filter as described earlier. During tale threading the generation of broke is high which accelerates the disc filter operation and more solids end up into the filtrates. Therefore, the applicability of SCF in the heat recovery loop should be evaluated based on stable production and discard the utilization near the disturbance events.

8.3 Microbial activity

The results of microbial activity experiments are presented in Table XI as retention of colony forming unit (CFU). These filtration experiments were unsuccessful to determine the genuine effect filtration has on microbial activity due to low microbial activity of SCF. However, based on these results, it can be concluded that the microbial activity in SCF is low and will not be prevent the utilization of SCF in the heat recovery loop to replace fresh water.

Table XI The retention of CFU in filtration of SCF. The reliability of the retentions is scarce due to low CFU in the filtration feed. The retention of filter cloths Nitex15 and Nitex41 were negative which means that the CFU was higher in the permeate than in the feed solution.

Sample	CFU retention, %
MV020	67 %
RC70PP	40 %
NF270	0 %

As can be observed from Table XI the retention is highest with MV020 and lowest with NF270. Tight membranes might retain compounds that inhibit the microbial growth which might explain the low CFU retention with NF membrane. It was found out that CFU is higher in the permeate than in the feed solution when filter cloths were used in filtrations. All the samples were treated the same way, so the increase of CFU in the filter cloth permeates might be due to cloth material or to contamination of samples. However, it might also be caused by retaining of microbial growth inhibiting compounds in filtration. Based on the CFU of the control sample the conditions did not increase the microbial activity in the sample. The experiments were not repeated which decreases the reliability of the results.

According to supplier’s measured data of microbial activity of BM1 process waters, SCF is applicable in the heat recovery loop with lower microbial activity than in other measured waters. So, regardless of the filtration method applied, SCF should be applicable in the heat recovery loop in relation to microbial activity. However, when SCF is applied in the loop, the microbial activity of process water and the product should be monitored in the beginning to avoid any issues.

8.4 Treatment of SCF by filtration

Filtration flux for each membrane is presented as function of permeate yield in Figure 25. As can be observed the flux is lowest with the RO membrane, BW30, and highest with the UF membrane, RC70PP. This is due to MWCO that is lowest of these membranes with RO membrane and highest with UF. The fluxes of NFX and BW30 are similar as are fluxes of UH004P and NF270. It can be concluded that MWCO is not the only parameter affecting the flux. Membrane characteristics and pressure applied in the filtrations also affect the flux. The pressure in filtration with NF270 was 4 bar when the pressure in filtration with UH004P was 5.5 bar. So, lower pressure could be applied with NF270 compared to UH004P and still the flux is almost the same with these membranes. The pressure applied in filtration with NFX and BW30 was the same being 5.5 bar.

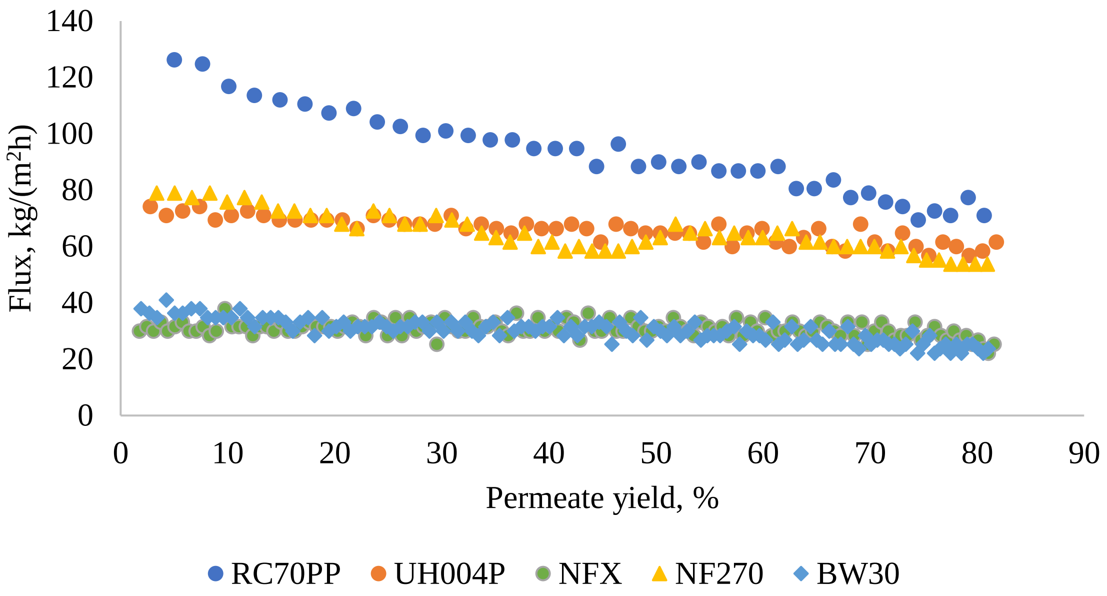

Figure 25 Filtration flux of different membranes as function of permeate yield. The pressures applied were 2 bar for RC70PP, 4 bar for NF270 and 5.5 bar for the rest of the membranes. The filtration volume was 300 ml and the membrane area 38 cm^2 in all the experiments.

In Table XII the pure water permeability (PWP) of each membrane is presented. Permeability of membrane is measured before filtration (PWP_b) and after filtration (PWP_a) in order to determine the effect filtration has on membrane. As can be seen from Table XII, permeability has decreased by little after filtration with every membrane except for NFX. Decreasing of permeability after filtration imply that fouling of membrane occurred. However, more experiments should be conducted before making more conclusions about fouling. The rise in permeability with NFX membrane might be due to lack of pretreatment of membrane.

Table XII Pure water permeability of membrane. The pressures applied are 2 bar for RC70PP, 5 bar for NF270 and 5.5 bar for other membranes. The filtration area was 38 cm^2.

Membrane	**PWP_b, kg/(m^2hbar)**	**PWP_a, kg/(m^2hbar)**
RC70PP	36.83	35.10
UH004P	7.12	7.00
NF270	11.54	9.14
NFX	2.86	3.16
BW30	3.86	2.65

The retention of COD and conductivity for each filtration experiment are presented in Figure 26. The highest retention of COD was achieved with BW30 and it was 92 %, and the highest retention of conductivity was achieved with the same membrane with retention of 86 %. The lowest COD retention of 4 % was with Nitex 41. There was no reduction of conductivity with Nitex 41 and RC70PP, and with UH004P the retention of conductivity was only 2 %. It can be concluded that the retention of COD and conductivity is higher with lower MWCO of membrane as Weise et al. (2008) presented. Fewer compounds pass through the membrane when the MWCO is lower. The exception is NF270 that has higher MWCO than NFX while the retention of COD is also higher, 81 %, than of NXF, 77 %. Because conductivity retention remained under 90 % even with the tightest membrane it can be deduced that there are a lot of monovalent ions present in the SCF.

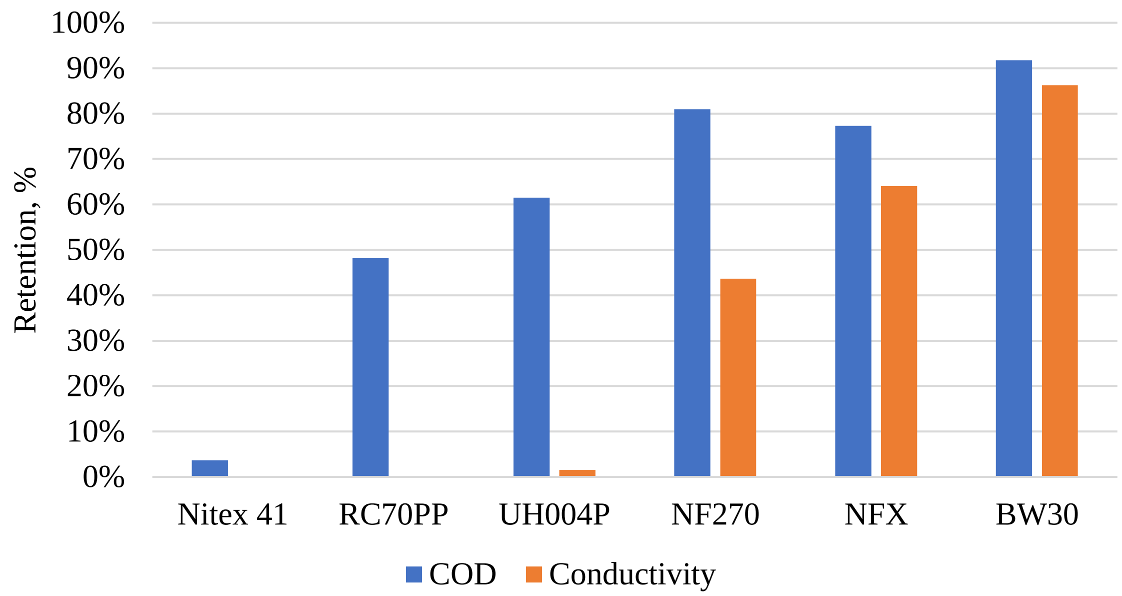

Figure 26 COD and conductivity retention in membrane filtration experiments with different membranes and a filter cloth.

The retention of SS was measured for the filter cloth. The SS concentration in the feed was 5.4 mg/l and in the filtrate 2.0 mg/l which makes the retention of SS 62 %. Frankly, the SS retention does not correlate to the solids removal of the shower water filter because the pore size of the cloth was much smaller than in the shower water filter. However, it is beneficial to prove that solids can be removed with the filter cloth. The retention of COD with Nitex 41 was only 4 % and there was no effect on conductivity. These results correlate with Weise et al. (2008) that describe that filter cloth removes some of SS, but tighter membrane is required to reduce also COD and conductivity.

When comparing the results obtained with filtrations to the measured clear shower water quality, it can be concluded that the tightest membrane is required in order to achieve the same purity. The average conductivity of clear shower water was 6.5 mS/m, pH 6.9 and COD 16.2 mg/l with deviations of 0.1, 0.3 and 0.9, respectively. No SS were discovered in the solids measurements from the clear shower water.

However, the requirement of the same purity is not necessarily obligatory but higher concentrations are allowed. Depending on whether the filtrate is combined with other water fraction or utilized in a separate line the filtrate might be diluted before application. When filtrate is diluted the impacts of disturbing compounds are smaller. In the case of BM1, there is an existing process line to apply SCF to curved screens as demonstrated in Figure 12. So, the filtrate would be combined with warm water rather than lead to a separate application.

In Chapter 3.3 the quality requirements of different type of water were reviewed. According to those requirements, it can be concluded that in order to apply SCF in high pressure shower applications, membrane filtration is required. In order to reach the high demands of high pressure shower water cost efficiently, different membrane technologies could be combined. However, the limits for utilizing SCF in other applications such as shower water and fresh water substituent are lower (Weise et al. 2008), and traditional filtration could be applied in the treatment of SCF. When considering the SS in SCF that settles to under 5 mg/l in the sampling period and under 4 mg/l in the entire year, it would be possible to utilize the filtrate without further treatment.

However, there are higher concentrations in the SCF as described earlier in the Chapters 8.2.2 and 8.2.4. Higher solids concentrations would cause clogging of shower nozzles if the water is not treated, and higher conductivity and COD could interfere on the wet end chemistry. Because the disc filter operation is quite complex and the impacts of the feed quality variations on filtrate quality cannot be fully predicted, it would be recommended to apply a police filter to treat the SCF. A police filter, that could be the shower water filter discussed earlier, would retain the occasional solids from the filtrate and prevent them from entering the shower nozzles. Another option would be to increase the capacity of the existing sand filtration unit or add another sand filtration to treat the SCF. As Thompson et al. (2016) reported, sand filtration is efficient in removal of SS and COD, and it is quite cost-efficient treatment technology. The next step of the water use optimization should be evaluation of the best possible treatment technology to treat the SCF and to fulfill the requirements of the filtrate quality cost-effectively.

Similarity to microbial activity, it is recommended to monitor these parameters when applying the SCF in the heat recovery loop. It is nearly impossible to determine the effects the change of water system will have on the overall production process which is why the monitoring is important. A trial run is recommended to monitor the effects.

8.5 Possibility of error

In determining the SWC in BM1 data was collected every minute, and the SWC in every year was determined from the average yearly water consumption based on the collected data. Especially in 2020 the monthly variation of water consumption was high which could be observed from the extreme values presented earlier. By determining the water consumption from the average values the absolute water consumption cannot be determined. However, the determined SWC is a reliable estimation of the water consumption, and to achieve more accurate results more explicit measurements of water flows are required. In the regard of this thesis the accuracy of the average values is sufficient.

Due to low solids concentration of SCF the influence of error in SS analysis is significant. Factors that may cause error in the results of SS analysis are sampling, sample handling, weighing, measurements and the effect of dust or impurities ending up in the sample. The factors that may cause error in the sampling are related to the ability to gather a representative sample. Before sampling the cleanliness of sampling valve was checked externally for dirt, and water was run from the valve before the sampling. The containers, where samples were collected, were thoroughly washed with deionized water before use and rinsed with SCF before sampling. The samples for the microbiological experiments were collected to sterile containers to avoid contamination of samples. Due to high generation rate of SCF and the size of the drop leg the turnover rate of SCF is high. This may increase the variation in the quality of samples taken only a few seconds apart from each other. In addition, the SS concentration is low and can vary greatly between samples if, for instance a fiber floc ends up in the sample.

The main factors that might cause error in the analyses are weighing and measuring. All samples were thoroughly shaken before the experiments in order to gather a representative sample from the sampling container. Due to low SS in SCF high volume was applied in the SS measurements. Although the dry residue was over 2 mg in the samples it was under 5 mg in many samples which may cause error in weighing. The filtration papers were put to oven as soon as possible after the filtration to avoid dust from contaminating the samples. The same applies for sample handling after drying and before weighing. But there is a possibility that dust has ended up in the sample and increased the dry matter by little. However, the effect of dust is considered small due to proper handling of samples. The instrumental error with used instruments, such as pipettes, is considered small due to proper operation. Before pipetting the sample to the COD tube, pipette was rinsed with the sample three times which should increase the reliability of the measured volume.

The samples were stored at room temperature in the sampling containers before filtration and microbiological experiments which could have affected the results. Due to quite short storing times, that were from 2 to 24 hours, it was not considered necessary to refrigerate the samples and then warm them up to room temperature before the analyses. The impact of storing the samples was analyzed through COD, pH and conductivity from few samples, and there was no effect observed from the storing time with the samples. It was conducted that the storing time does not affect the results of these parameters, but the result should be construed with precaution because the storing of samples does not follow the standard SFS-EN 872 (2005). In microbiological experiments the effect of storing the samples was not analyzed, but as mentioned earlier, all the samples were analyzed withing 24-hours of sample taking. However, this may cause error in microbiological analyses.

In membrane filtrations the only pretreatment of membrane was soaking in deionized water and pressurizing before the filtration. No chemical washing was done to the membranes prior to use. Cutting out the chemical treatment of membranes may affect the permeability of membrane and the filtration retentions. Thus, permeabilities of membranes should be considered with precaution. The impact on retention was considered to be minor, and because the determination of retention was the main focus of the experiments it was not considered necessary to treat the membranes chemically before the experiments.

9 FINAL CONCLUSIONS

In this thesis the possibilities for water consumption optimization in BM1 were determined. Papermaking consumes huge amounts of water in its processes which affects the sustainability of the produced products. Over the years the production process has been developed into more sustainable by increasing the water recycling. Water is circulated in the mills to decrease the fresh water consumption, wastewater generation and also the costs related to water treatment, transportation and heating. The reduction of fresh water use has adduced runnability and quality problems in the production process due to enrichment of disturbing substances in the circulation waters when proper treatment of water has not been applied. More actions can be established to increase the sustainability of papermaking and enhance the recycling rate of water by internal treatment of circulation waters.

The experimental part of the thesis surveyed the water consumption of BM1 at Stora Enso Imatra Mills. The specific water consumption of BM1 was determined, and the optimization opportunity of water use was discovered in the utilization of super-clear filtrate from the disc filter. Currently, SCF is utilized in the white water loop at BM1. Due to the purity of the filtrate there could be potential to apply the filtrate to the heat recovery loop where the water purity demand is high. This would reduce wastewater generation by decreasing the water overflow from water storages and also reduce the fresh water use. It was determined that by applying 50 % of the generated SCF to the heat recovery loop, the SWC could be reduced by 30 %.

Based on the quality analysis of the SCF, it was concluded that treatment is recommendable before applying the filtrate in the heat recovery loop to ensure adequate purity. The average SS in SCF was 5 mg/l based on the sampling period, and respectively, 6 mg/l based on the yearly measurements in 2020. The average conductivity was 56 mS/m, pH was 4.4 and COD 220 mg/l. The measured values for clear shower water that the SCF is compared to was for conductivity 6.5 mS/m, pH 6.9 and COD 16.2 mg/l. The values are much lower in the clear shower water than in SCF which resulted in recommendation of treatment of SCF. No SS were discovered in the solids analysis of clear shower water. The microbial activity of the SCF was determined to be minor and would not prevent the use of SCF as shower water.

Membrane technology was applied in treatment of the filtrate at laboratory scale, and it provided promising results with respect to removal of SS, COD and conductivity. As high as 92 % of COD retention and 86 % of conductivity retention was achieved with the RO membrane. The two NF membranes reached 81 % and 77 % of COD retention and 44 % and 64 % of conductivity retention. The two UF membranes applied reached 48 % and 62 % of COD retention but the conductivity retentions were nearly zero. Besides the membrane technology also filtration with filter cloth was experimented. Filtration experiments with a filter cloth indicated quite high removal of SS, that is 62 %, but a lack of removal of COD and conductivity.

By recognizing the process situations that decrease the quality of SCF and controlling the filtrate use based on that knowledge, filtrate could possibly be utilized without further treatment. These situations are related to web breakage and sudden increase of broke feed to the disc filter. Additionally, it was detected that broke pulping affects highly on filtrate quality. Pulping of broke should kept steady to achieve the highest purity of filtrates. By maintaining a stable feed of broke to the disc filter, the consistency and the filter surface should stay stable which improves the capacity of the filter.

The means to minimize the risks related to the use of SCF in the heat recovery loop were discovered in the proper treatment SCF. Membrane technology is an efficient treatment method but quite expensive one which is why also other filtration technologies should be considered. Thereby, a police filter or sand filtration is recommended to ensure the sufficient quality of SCF and to retain the solids that pass through the disc filter. There is an existing sand filtration unit in the heat recovery loop that would obtain the solids and decrease the COD of SCF. So, another option is to increase the capacity of sand filtration unit to treat the water efficiently.

The papermaking process is very complex and even small changes can affect the wet end chemistry. The impacts of white water composition on the production process were reviewed in Chapter 3.1.1 in regard of SS and in Chapter 3.1.2 in regard of DCS. Because trial runs of applying SCF in the heat recovery loop were not carried out in this thesis, trial runs are recommended in the future. Within the trial runs further knowledge is attained and, a full understanding of the small changes of filtrate quality can be obtained. The capacity of sand filtration unit and curved screens must be determined as well as the water quality after sand filtration and screening. When applying SS to use, SS should be measured more often than in this experiment to monitor and fully identify the changes and the effect the changes have on the production process and the product quality.

REFERENCES

Alakomi, H-L., Kujanpää, K., Partanen, L., Suihko, M-L., Salo, S., Siika-aho, M., Saarela, M., Mattila-Sandholm, T., & Raaska, L. 2002. Microbiological problems in paper machine environments. VTT Technical Research Centre of Finland. *VTT Tiedotteita - Meddelanden - Research Notes*. No. 2152. pp. 1-97.

Alexandersson, T. & Malmqvist, Å. 2005. Treatment of packaging board whitewater in anaerobic/aerobic biokidney. *Water Science & Technology*. Vol. 52(10-11), pp. 289-298.

Alfa Laval. 2021. Alfa Laval UF flat sheet membranes [e-document]. [Referred 19.3.2021]. pp. 1-2. Available in: https://www.alfalaval.com/globalassets/documents/products/separation/membranes/flat-sheet-membranes/uf-flat-sheet-membranes_200000311-4-en-gb.pdf

Amat, A., Arques, A., Miranda, M. & López, F. 2005. Use of ozone and/or UV in the treatment of effluents from board paper industry. *Chemosphere*. Vol. 60(8), pp. 1111-1117.

Auhorn, W. 2006. Chemical Additives. In: Holik, H. (ed.), *Handbook of Paper and Board*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA. pp. 62-149. ISBN 3-527-30997-7.

Bajpai, P. 2010. Wastewater Treatment for Water Recovery and Reuse. In: Bajpai, P., *Environmentally Friendly Production of Pulp and Paper*. New Jersey, USA: John Wiley & Sons, Inc. pp. 281-305. ISBN 978-0-470-52810-5.

Blanco, Á., Hermosilla, D. & Negro, C. 2015. Water Reuse Within the Paper Industry. In: Fatta-Kassinos, D., Dionysiou, D. & Kümmerer, K. (ed.), *Wastewater Reuse and Current Challenges* [e-book]. Cham: Springer International Publishing. The Handbook of Environmental Chemistry. Vol. 44, pp. 213-237. ISBN 978-3-319-23892-0.

Blanco, Á., Hermosilla, D., Monte, M. & Negro, C. 2016. White Water Recovery by Membrane Operations. In: Driolin, E. & Giorno, L. (ed.), *Encyclopedia of Membranes* [e-book]. Berlin, Germany: Springer-Verlag. ISBN 978-3-662-44325-5.

BREF Integrated Pollution Prevention and Control (IPPC). 2015. Reference Document on Best Available Techniques (BAT) for the Production of Pulp, Paper and Board. European Commission. JRC Science and Policy Reports. ISBN 978-92-79-48167-3.

Choi, S., Kim, H., Kim, Y., Park, H. & Englezos, P. 2003. Gypsum Scale Formation in White Water of a Closed-Cycled Paper Mill. *The Canadian Journal of Chemical Engineering*. Vol. 81, pp. 1083-1086.

Dahl, O. 2008. Process modifications to reduce effluent loads. In: Dahl, O. (ed.), *Environmental Management and Control*. 2nd edition. Helsinki, Finland: Finnish Paper Engineers' Association. pp. 69-84. Papermaking Science and Technology, Book 19. ISBN 978-952-5261-30-1.

Dilek, G. & Gökçay, C. 1994. Treatment of Effluents from Hemp-Based Pulp and Paper Industry I. Waste Characterization and Physico-Chemical Treatability. *Water Science & Technology*. Vol. 29(9), pp. 161–163.

Elliot, A. & Mahmood, T. 2007. Whitewater (WW) quality and treatment options for closing value added WW loops. *Pulp & Paper Canada*. Vol. 108(11), pp. 26-31.

Gupta, A. & Gupta, R. 2019. Treatment and Recycling of Wastewater from Pulp and Paper Mill. In: Sighn, R.L. & Sighn. R.P. (ed.), *Advances in Biological Treatment of Industrial Waste Water and their Recycling for a Sustainable Future* [e-book]. Singapore: Springer Nature Singapore Pte Ltd. Applied Environmental Science and Engineering for a Sustainable Future. pp. 13-50. ISBN 978-981-13-1468-1.

Häggblom-Ahnger, U. & Komulainen, P. 2005. *Paperin ja kartongin valmistus*. 3nd edition. Helsinki, Finland: Opetushallitus. pp. 8-239. Kemiallinen metsäteollisuus II. ISBN 952-13-1746-9.

Hermosilla, D., Merayo, N., Gascó, A. & Blanco, Á. 2015. The application of advanced oxidation technologies to the treatment of effluents from the pulp and paper industry: a review. *Environmental Science & Pollution Research International.* Vol. 22(1), pp. 168-191.

Holik, H. 2006. Stock Preparation. In: Holik, H. (ed.), *Handbook of Paper and Board*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA. pp. 62-149. ISBN 3-527-30997-7.

Honkamaa, J. & Käki, P. 2008. Vacuum pumps. In: Paulapuro, H. (ed.) *Papermaking Part 1, Stock Preparation and Wet End*. 2nd edition. Helsinki, Finland: Finnish Paper Engineers' Association. pp. 494-510. Papermaking Science and Technology, Book 8. ISBN 978-952-5216-25-7.

Hubbe, M. 2007. Water and Papermaking – 3. Measures to Clean Up Process Water. *Paper Technology*. Vol. 48(3), pp. 23-30.

Hubbe, M., Metts, J., Hermosilla, D., Blanco, Á., Yerushalmi, L., Haghighat, F., Lindholm-Lehto, P., Khodaparast, Z., Kamali, M. & Elliott, A. 2016. Water Treatment and Reclamation: A Review of Pulp and Paper Industry Practices and Opportunities. *BioResources*. Vol. 11(3), pp. 7953-8091.

Huster, R., Demel, I. & Geller, A. 1991. Closing paper mill whitewater circuits by increasing an anerobic stage with subsequent treatment. *Water Science & Technology*. Vol. 24(3), pp. 81-90.

Hynninen, P. 2008a. Effluent treatment. In: Dahl, O. (ed.), *Environmental Management and Control*. 2nd edition. Helsinki, Finland: Finnish Paper Engineers' Association. pp. 85-116. Papermaking Science and Technology, Book 19. ISBN 978-952-5261-30-1.

Hynninen, P. 2008b. Raw water treatment. In: Dahl, O. (ed.), *Environmental Management and Control*. 2nd edition. Helsinki, Finland: Finnish Paper Engineers' Association. pp. 56-68. Papermaking Science and Technology, Book 19. ISBN 978-952-5261-30-1.

Jamil, T., Ghaly, M., El-Seesy, I., Souaya, E. & Nasr, R. 2011. A comparative study among different photochemical oxidation processes to enhance the biodegradability of paper mill wastewater. *Journal of Hazardous Materials*. Vol. 185(1), pp. 353-358.

Karlsson, M. & Paltakari, J. 2010. Introduction to paper drying and its principles. In: Karlsson, M. (ed), *Papermaking Part 2, Drying*. 2nd edition. Helsinki, Finland: Finnish Paper Engineers' Association. pp. 13-38. Papermaking Science and Technology, Book 9. ISBN 978-952-5216-37-0.

Kiviranta, A. 2000. Paperboard grades. In: Paulapuro, H (ed.), *Paper and Board Grades*. Helsinki, Finland: Fapet Oy. Papermaking Science and Technology, Book 18. pp. 55-72. ISBN 952-5216-18-7.

Knuutinen, J. & Alén, R. 2007. Overview of analytical methods in wet-end chemistry. In: Alén, R. (ed.), *Papermaking Chemistry*. 2nd edition. Helsinki, Finland: Finnish Paper Engineers' Association. pp. 199-228. Papermaking Science and Technology, Book 4. ISBN 978-952-5216-24-0.

Lacorte, S., Latorre, A., Barceló, D., Rigol, A., Malmqvist, A. & Welander, T. 2003. Organic compounds in paper-mill process waters and effluents. *Trends in Analytical Chemistry*. Vol. 22(10), pp. 725-737.

Latorre, A., Malmqvist, A., Lacorte, S., Welander, T. & Barceló. 2007. Evaluation of the treatment efficiencies of paper mill white waters in terms of organic composition and toxicity. *Environmental Pollution*. Vol. 147(3), pp. 648-655.

Laufmann, M. 2006. Pigments as Fillers. In: Holik, H. (ed.), *Handbook of Paper and Board*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA. pp. 33-55. ISBN 3-527-30997-7.

Marttinen, P. 2000. Kartonkikoneen vesiselvitys. Stora Enso. Internal material.

Microdyn-Nadir. 2020a. Nadir MV020 T – Microfiltration Membrane [e-document]. [Referred 19.3.2021]. Available in: https://www.microdyn-nadir.com/wp-content/uploads/MV020-T-Flat-Sheet-Membrane.pdf

Microdyn-Nadir. 2020b. Nadir UH004P – Ultrafiltration Membrane [e-document]. [Referred 19.3.2021]. Available in: https://www.microdyn-nadir.com/wp-content/uploads/UH004-P-Flat-Sheet-Membrane.pdf

Mulder, M. 1996. *Basic Principles of Membrane Technology*. Dordrecht, The Netherlands: Kluwer Academic Publishers. pp. 1-21, 280-306. ISBN 978-94-009-1766-8.

Nassar, M. 2003. Studies on internal and external water treatment at a paper and cardboard factory. *Journal of Chemical Technology and Biotechnology (1986)*. Vol. 78(5), pp. 572-576.

Nuortila-Jokinen, J. 1995. The closed paper mill white water system and the internal paper mill white water treatment. Lappeenranta, Finland: Lappeenranta University of Technology. pp.1-27. Lappeenranta University of Technology, Department of Chemical Technology, 59.

Nuortila-Jokinen, J., Mänttäri, M., Kallioinen, M. & Nyström, M. 2004. Water circuit closure with membrane technology in the pulp and paper industry. *Water Science & Technology*. Vol. 50(3), pp. 217-227.

Pitkänen, M., Mannström, M., Lumiainen, J. & Lundin, T. 2009. Thickening, storage and post-refining. In: Lönnberg, B (ed.), *Mechanical Pulping*. 2nd edition. Helsinki, Finland: Paper Engineers' Association. pp. 399-418. Papermaking Science and Technology, Book 5. ISBN 978-952-5216-35-6.

Räisänen, K. 2008. Vacuum systems. In: Paulapuro, H. (ed.) *Papermaking Part 1, Stock Preparation and Wet End*. 2nd edition. Helsinki, Finland: Finnish Paper Engineers' Association. pp. 478-492. Papermaking Science and Technology, Book 8. ISBN 978-952-5216-25-7.

Sefar. 2007. Open Mesh Fabrics - Precision Woven Synthetic Monofilament Fabrics [e-document]. [Referred 15.3.2021]. p. 7. Available in: https://www.sefar.com/data/docs/ru_RU/5160/FS-PDF-IF-TL-Open-mesh-fabrics-RU.pdf?v=1.0

Seppälä, M. (ed.). 2002. *Paperimassan valmistus*. 2nd edition. Helsinki, Finland: Opetushallitus. pp. 168-186. ISBN 952-13-1142-8.

SFS-EN 872. 2005. Water quality. Determination of suspended solids. Method by filtration through glass fibre filters. Helsinki: Finnish Standards Association. pp. 10.

Shammas, N., Wang, L. & Landin, M. 2010. Treatment of Paper Mill Whitewater, Recycling and Recovery of Raw Materials. In: Wang, L., Shammas, N., Selke, W. & Aulenbach, D. (ed.), *Flotation Technology* [e-book]. New York, USA: Humana Press. Handbook of Environmental Engineering, Volume 12. pp. 221-268. ISBN 978-1-60327-133-2.

Snyder Filtration. 2021. NFX (TFC 150-300 Da) – Industrial NF Membrane [e-document]. [Referred 19.3.2021]. Available in: https://synderfiltration.com/2014/wp-content/uploads/2018/07/NFX-TFC-150-300Da-Industrial-Specsheet.pdf

Sparks, T. & Chase, G. 2016. *Filters and filtration handbook.*6th edition. Oxford, England: Butterworth-Heinemann. pp. 204-237. ISBN 0-08-099400-8

Stenius, P. 2000. Macromolecular, surface, and colloidal chemistry. In: Stenius, P. (ed.) *Forest Products Chemistry*. 1st edition. Helsinki, Finland: Finnish Paper Engineers' Association. pp.173-278. Papermaking Science and Technology, Book 3. ISBN 952-5216-03-9.

Sterlitech. 2020a. Nanofiltration (NF) Membranes [webpage]. Membrane/Process Development - Flat Sheet Membranes. [Referred 19.3.2021]. Available in: https://www.sterlitech.com/nanofiltration-nf-membrane.html

Sterlitech. 2020b. Dow Filmtec Flat Sheet Membrane, BW30LE, PA-TFC, RO, CF016, 5/Pk [webpage]. Membrane/Process Development – Flat Sheet Membranes. [Referred 19.3.2021]. Available in: https://www.sterlitech.com/dow-filmtec-flat-sheet-membrane-bw30le-pa-tfc-ro-cf016-5-pk.html

Stetter, A. 2006. Water Circuits. In: Holik, H. (ed.), *Handbook of Paper and Board*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA. pp. 208-218. ISBN 3-527-30997-7.

Stora Enso. 2019. Material Cards [e-document]. About Our Products. [Referred 28.4.2021]. Available in: Stora Enso internal website.

Stora Enso. 2021a. Imatran tehtaiden tuotanto [website]. Imatra Mills. [Referred 28.4.2021]. Available in: Stora Enso internal website.

Stora Enso. 2021b. Key Facts [e-document]. Company Products. [Referred 28.4.2021]. Available in: Stora Enso internal website.

Tenno, R. & Paulapuro, H. 1999. Removal of dissolved organic compounds from paper machine whitewater by membrane bioreactors: a comparative analysis. *Control Engineering Practice*. Vol. 7, pp. 1085-1099.

Thompson, N., Onyebuchi, N., Theophilus, A., Jerry, U. & Chizoba, A. 2016. Laboratory Studies on the Treatment of Effluent from a Pulp and Paper Mill Using Activated Carbon and Sand Filter Media. *American Chemical Science Journal*. Vol. 12(1), pp. 1-14.

Valmet Oy. 1997. *Kartonkikoneet*. 2nd edition. Vantaa, Finland: Sepsilva LTD Oy. Puusta paperiin. pp.42-123, 155-173. ISBN 951-9309-79-9.

Valmet. 2021a. Valmet Disc Filter CDI [web page]. Board and paper. [Referred 29.4.2021]. Available in: https://www.valmet.com/board-and-paper/stock-preparation/white-water-system/Filtration-technology/disc-filter-cdi/

Valmet. 2021b. Valmet Fiber Image Analyzer [web page]. Automation. [Referred 13.4.2021]. Available in: https://www.valmet.com/automation/analyzers-measurements/analyzers/fiber-image-analyzer-for-external-fibrillation-fiber-length-measurement/

Weise, U., Terho, J., Paulapuro, H., Käki, P., Leppänen, P. & Oksanen, N. 2008. Stock and water systems of the paper machine. In: Paulapuro, H. (ed.) *Papermaking Part 1, Stock Preparation and Wet End*. 2nd edition. Helsinki, Finland: Finnish Paper Engineers' Association. pp.140-215. Papermaking Science and Technology, Book 8. ISBN 978-952-5216-25-7.

Yen, N., Oanh, N., Reutergardh, L., Wise, D. & Lan, N. 1996. An integrated waste survey and environmental effects of COGIDO, a bleached pulp and paper mill in Vietnam, on the receiving waterbody. *Resources, Conservation and Recycling*. Vol. 18(1), pp. 161-173.

DATES AND TIMES OF SAMPLING.

Table I Dates and times of sampling of SCF.

Date	**Time**				**Experiment**
8-Feb	8:40	18:10			Microbial activity
19-Feb	15:25				Water quality
22-Feb	9:05	13:00	16:05		Water quality
23-Feb	8:00	10:05	13:10	14:45	Water quality
24-Feb	8:30				Water quality
2-Mar	8:00	9:10	13:00	15:30	Water quality
3-Mar	12:45	13:55			Water quality
4-Mar	9:45	11:20	12:30	15:30	Water quality
5-Mar	7:45	9:50			Water quality
8-Mar	14:30				Filtrations
19-Mar	14:00				Filtrations
27-Mar	8:56				Water quality

Table II Dates and times of sampling of clear shower water.

Date	**Time**	**Experiment**
24-Feb	8:27	Water quality
2-Mar	7:55	Water quality
2-Mar	9:05	Water quality
2-Mar	15:35	Water quality