LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Engineering Science
Master’s Programme in Chemical and Process Engineering

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EXAMINATION OF BOARD MACHINE WATER CONSUMPTION AND ITS REDUCTION POTENTIAL

Examiners: Adjunct Professor Arto Laari
Associate Professor Ritva Tuunila
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ABSTRACT

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Examination of board machine water consumption and its reduction potential

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82 pages, 22 figures, 8 tables and 1 appendix

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Keywords: board mill, water consumption, white water, super clear filtrate

The aim of this work was to find out the water fractions used at Stora Enso Imatra mills' board machine 4, map the applications in which the selected water fractions are utilized, and examine for which purposes the waters are used in these applications. Furthermore, the possibilities to reduce water consumption at the board machine were searched.

In the literature part of this work the related literature was gone through and several topics were discussed based on it. Amongst other, the topics included the board process and chemicals involved, properties of the board, the water system of board machine, water consumption and its reduction possibilities, different water fractions and water treatment methods. In addition, Stora Enso Imatra mills and board machine 4 were briefly introduced.

In the experimental part the water system of board machine 4 and the used water fractions were studied. Average consumptions of five water fractions were determined from one year period, and four of the water fractions were selected for mapping the applications that consume these waters. Filtrate water filter was selected as a subject of study to examine the reduction of water consumption. Super clear filtrate coming from a disc filter is filtrated through the filtrate water filter and used as shower water. A test run was conducted to find out if the proportion of super clear filtrate can be increased in the shower water. By increasing the use of super clear filtrate, the consumption of fresh water can be decreased.

The studies of the experimental part showed that the current values for washing time and the time between washes of the filtrate water filter, and the opening of the valve restricting the flow through the filter are somewhat optimal, and by changing the values of these operational parameters the use of super clear filtrate cannot be significantly increased. More of the super clear filtrate could be utilized in the shower water by increasing the surface area of the filtration.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
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Kemiantekniikan koulutusohjelma

Iiro Viitanen

Kartonkikoneen vedenkulutuksen tutkiminen ja vähentämismahdollisuudet

Diplomityö

2021

82 sivua, 22 kuvaa, 8 taulukkoa ja 1 liite

Tarkastajat: Dosentti Arto Laari
Tutkijaopettaja Ritva Tuunila

Hakusanat: kartonkitehdas, vedenkulutus, kiertovesi, superkirkassuodos

Tämän työn tarkoituksena oli selvittää Stora Enson Imatran tehtaiden kartonkikone 4:llä käytettävät vesijakeet, kartoittaa valittujen vesijakeiden käyttökohteet sekä vesijakeiden käyttötarkoitukset kyseisissä kohteissa. Lisäksi tuli selvittää kartonkikoneen vedenkäytön vähentämismahdollisuuksia.

Kirjallisuusosassa on käyty läpi aihepiiriin liittyvää kirjallisuutta ja kuvattu sen pohjalta muun muassa kartongin valmistusprosessia ja siinä käytettyjä kemikaaleja, kartongin ominaisuuksia, kartonkikoneen vesijärjestelmää, vedenkulutusta ja sen vähentämismahdollisuuksia, erilaisia vesijakeita ja veden puhdistusmenetelmiä. Lisäksi Stora Enson Imatran tehtaat ja kartonkikone 4 on esitelty lyhyesti.

Kokeellisessa osassa tutustuttiin kartonkikone 4:n vesijärjestelmään ja selvitettiin käytössä olevat vesijakeet. Viiden vesijakeen keskimääräiset kulutukset selvitettiin vuoden ajalta, ja vesijakeista neljä valittiin niiden käyttökohteiden kartoitukseen. Tutkimuskohteeksi vedenkulutuksen vähentämiselle valittiin suodosvesisuodin, joka suodattaa kiekkosuotimelta tulevaa superkirkassuodosta. Suodatettua superkirkassuodosta käytetään suihkuvedessä. Tarkoituksena oli koeajon avulla selvittää, voitaisiinko superkirkassuodoksen osuutta lisätä, jolloin voitaisiin vähentää tuoreveden kulutusta.

Kokeellisen osan tutkimukset osoittivat, että nykyiset suodattimen pesuajat ja -välit sekä suodattimen läpi menevää virtausta rajoittavan venttiilin aukeama ovat jokseenkin optimaaliset, eikä niitä muuttamalla voida juuri lisätä superkirkassuodoksen hyötykäyttöä suihkuvedessä. Superkirkassuodosta voitaisiin hyödyntää suihkuvedessä nykyistä enemmän kasvattamalla suodatuspinta-alaa.

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Imatra, 28.5.2021

Iiro Viitanen

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List of abbreviations

AKD	Alkyl ketene dimer
AOX	Adsorbable organic halogens
ASA	Alkenyl succinic anhydride
BAT	Best available techniques
BM4	Board machine 4
BOD	Biological oxygen demand
COD	Chemical oxygen demand
CTMP	Chemithermomechanical pulp
DCS	Dissolved and colloidal substances
FBB	Folding boxboard
SBS	Solid bleached sulphate board
SUB	Solid unbleached sulphate board
LPB	Liquid packaging board

1 INTRODUCTION

In production of paper and board a significant amount of water is used, although the trend is decreasing. Paper and board mills consume fresh water often at amounts of 2-20 m^3/t paper, although the consumption can be close to 100 m^3/t for certain mills producing specialty or technical papers (Weise, et al., 2008). The water consumption has reduced from the past since the processes have improved, equipment has become more efficient, and water fractions of different quality are circulated and utilized. In this work the water fractions mean water streams of different types that are used in the production of board. Closing the water circulations and using the clarified process water instead of fresh water has played an important role in the reduction of fresh water use (Stetter, 2006b). Closure of the water circulations can cause new problems as the amount of impurities in the circulating waters is increased. These substances can precipitate on surfaces, effect to the quality of the product and to the operation of the board machine, for example.

It is important to continue reducing the fresh water consumption for several reasons. The water is limited natural resource, which needs treatment before and after its use in the manufacturing process of paper and board. Both water treatments generate costs and using less of the fresh water generates less effluents and decreases the energy consumption, which encourages to reduce the water consumption. Also, legislation and regulations steer the consumption of the fresh water and the amount of discharges in a lower direction (Weise, et al., 2008). In addition to savings, one reason for aiming to lower water consumption is the scarcity of water since the water sources vary depending on the location. To reduce the water consumption, best available techniques (BAT) can be utilized. In European Union there are BAT Reference documents which help to select suitable techniques for reducing emissions and wastes in the pulp and paper industry (Dahl, 2008a). As more attention is nowadays given to the condition of the environment, reducing the water consumption helps to protect the water bodies, and the environment overall as consumption is reduced.

1.1 The aim and scope of this study

This work was carried out at Stora Enso Imatra mills board machine 4 (BM4), which produces liquid packaging board, tray board and cup stock (Stora Enso, 2021b). Previously

Mälkiä (2015) has studied the possibility to reduce freshwater usage of BM4 by utilizing chemically treated wastewater. In that study the water balance of BM4 was determined, to find out where the water is being used and how much it is needed. Also, the properties of chemically treated wastewater were compared to those of the process waters, to see if there are some obstacles for reusing the water. The study revealed that because of the water's properties (solids-, sulphate- and carbonate content, microbial count, and colour), the chemically treated wastewater is not directly applicable to be used at BM4.

The reduction of freshwater consumption at BM4 was previously examined also by Pöyry (2014). In their investigation report the freshwater consumption for different applications at the board machine was measured, and possible targets for reducing the freshwater consumption were presented. It was stated in the report that the greatest savings could be achieved by discontinuing the freshwater intake from the warm water tank to the shower water tank, which could be implemented by improving the quality of filtrates of disc filter, or by improving the operation of filtrate water filter or by adding its filtration capacity.

The aim of this work was to describe which water fractions are used at board machine four, where they are used, and what are the purposes for which they are used at these applications. Because there are several water fractions used at BM4 and the number of pipelines is vast, the study was limited to four essential water fractions having the highest consumption. Furthermore, new ways to optimize the water usage needed to be searched. The optimization in this case means reduction or improvement in water usage in some way, such as reusing cleaner process waters again in applications where the required water purity level is lower. To protect some of the mill's information, the water streams are renamed, and the water flows are given in percentages.

Since the situation has changed in last five years, it is essential to make a new study to list the current applications which consume the different water fractions, and to list the purposes for which the waters are being used, and to find new ways to reduce the water consumption. The list of applications consuming the waters will help to find new ways for reducing the water consumption in the future.

1.2 Structure of this study

This work is split into two parts, literature part and experimental part. In the literature part, the basic theory supporting the work has been gone through using the existing literature. First, a quick overview of the board manufacturing process is gone through, and a few words about the board and its properties are mentioned. Some chemicals used in the manufacturing process are introduced to understand what chemicals might end up in the process waters. Then the water consumption of board process, the water system and broke system of a board machine are discussed. Different water fractions of a board mill, impurities in white water, and treatment of different board process waters are described. Finally, the reduction of board machine water consumption is discussed, and Imatra mills and the BM4 are described in general. Since board machines are similar to paper machines, and part of the found literature focused on the paper machines, as a result some of the information in literature part is based on the paper machines.

In the experimental part the different water fractions at the BM4 are discussed and consumptions of water fractions are analysed. The applications using selected water fractions are mapped. The possibility to increase the use of super clear filtrate in shower water tank to reduce the water intake from warm water tank was examined by conducting a test run. In the test run the super clear filtrate flow was increased through a filtrate water filter by adjusting a valve opening, and data from solids content measurements and online meters was examined.

2 BOARD PROCESS

In this section the manufacturing process of board is discussed. Board mills can vary significantly in design, but the basic idea behind the manufacturing process is the same, and the aim of this section is to give a quick overview of the operation of a board process.

The pulp, from which the board is made, is produced at a pulp mill. There are several types of pulp that can be used as raw materials for board. These include chemical pulps, mechanical pulps, and recycled fibre pulp, which all differ in their properties (Häggblom-Ahnger & Komulainen, 2006). The chemical pulps are often sulphate pulps, which are brown in colour if they are not bleached. Softwood sulphate pulp gives the board good strength properties, whereas the hardwood sulphate pulp can be used for better printability. The recycled fibre pulps and their processing are not discussed in this work.

The pulp is transported to the board mills either in bales, as flash dried flakes, or as a suspension in integrated mills, where the pulp mill is located at the same area with the board mill (Holik, et al., 2006; Stetter, 2006a). After the pulp is delivered to the board mill, the next step is the stock preparation. The stock is prepared from the pulps and other raw materials, such as fillers, pigments and chemical additives.

Stock preparation starts with the bale handling, if the pulp is delivered as bales (Lumiainen & Harju, 2008). The wires are removed from the bales and the bales are processed so that they can be fed into the pulper in the next step, which is slushing. In slushing, the pulp bales are slushed with water in a pulper. The pulper uses rotor to disintegrate the bales, and as a result, a suspension of fibres is formed. This can be then pumped forward to a pulper dump chest from which it can be led first to a deflaker, if a better defibration of the fibres is needed. The deflaker disintegrates the remaining fibre bundles and flakes and turns them into flexible and wetted fibres. From there the suspension is pumped to refiner feed chest. Impurities are removed before deflakers and refiners to avoid mechanical damage (Stetter, 2006a).

The refining of pulps is done in refiners, in which the fibres are led between the refiner blades, and the fibres are modified so that they are better able to form new bonds (Häggblom-Ahnger & Komulainen, 2006). Refining can be used to change the properties of the fibres as needed to suit the product better (Stetter, 2006a). These properties include for example the paper formation, and strength-, and optical properties. Refining also affects the runnability of the machine. After refining the suspension is pumped to blending chest (Häggblom-Ahnger & Komulainen, 2006). From blending chest, the stock is led to machine chest and into the short circulation of a board machine, and finally to the machine's headbox. The short circulation is discussed separately later in this text.

Board manufacturing process is similar to the process used to make paper (Häggblom-Ahnger & Komulainen, 2006). At the board machine the process starts from the wet end, which consists of headbox, wire section and press section. It is followed by the drying section, which can include surface-size press, coating heads or a Yankee cylinder. After drying, the board is calendered and winded into machine reels. This is demonstrated in Figure 1.

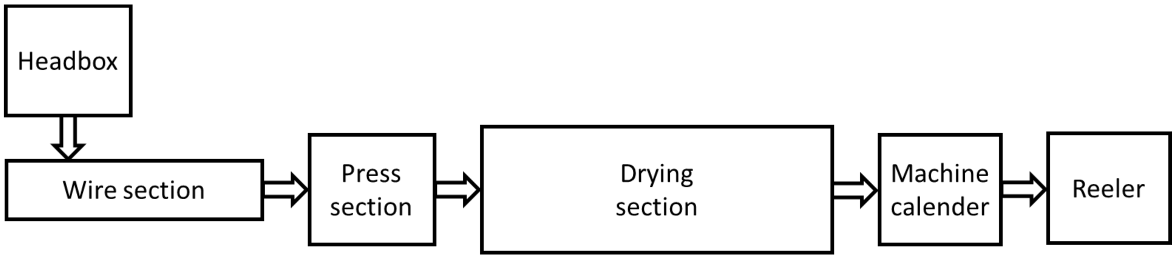

Figure 1. The basic construction of a board machine. Modified from (Häggblom-Ahnger & Komulainen, 2006)

The headbox is the part of board machine where the stock is fed, and it is used for spreading the stock uniformly on the wire (Häggblom-Ahnger & Komulainen, 2006; Norman, 2008). Before the stock enters the headbox it is diluted to desired consistency, which is around 1 % (Häggblom-Ahnger & Komulainen, 2006). The headbox is designed in a way that it creates turbulence and shear forces to break down the flocs in the stock and makes the stock more uniform before it is spread on the wire. A tapered channel is used to distribute the flow evenly in the headbox and from there to the wire. The headbox also evens out changes in inlet pressure. Several variations of headboxes exist, but they are not discussed here. If multiply board is made, then each layer needs its own headbox, wire and feedline for the stock.

In the beginning of the wire section dilute stock from headbox is spread on the wire, which is a plastic woven fabric (Häggblom-Ahnger & Komulainen, 2006). The web forms on the wire as most of the water contained in the stock is filtered through. In the wire section more than 95 % of the water directed to the headbox is separated and fed to short circulation, which is used for dilution of stock and for returning the raw materials contained in the circulation water back to use. Traditionally the water is removed from below using a fourdrinier machine in the wire section, but if more symmetrical product is desired, a twin wire machine can be used (Häggblom-Ahnger & Komulainen, 2006; Norman, 2008). It removes the water not only from the below, but also from the top, and it has higher capacity for water removal, which allows the twin wire machine to run at higher speeds than the fourdrinier machine. The web formed in the wire section can have dry solids content up to 20 %.

The wire section is followed by press section, where the web is directed between press rolls with one or two felts (Häggblom-Ahnger & Komulainen, 2006). As the web enters the nip, the applied pressure causes part of the water to leave the web, drying it. In addition to the water removal, the fibres bind more strongly to each other because of the applied pressure. Usually 2-4 press nips are used in press section and the dry solids content of the web is around 40-60 % after the press section. The press section is followed by the drying section where heat is used for drying the web, and in order to save steam energy, it is better to achieve highest possible dryness already at the press section.

Drying section can be constructed of multiple cylinders which are heated with steam (Häggblom-Ahnger & Komulainen, 2006). They are placed under a hood to recover the heat coming from the cylinders. Using wires, the web is led to the surfaces of the cylinders, which causes the water to evaporate from the web. To avoid the sticking of the web on the cylinders, the temperature of the first cylinders is kept lower than the following cylinders. Coating for the board can be applied at the drying section before the board is calendered, to achieve good printing quality. The board shrinks the most at the drying section.

After drying, the board is calendered (Häggblom-Ahnger & Komulainen, 2006). In this part of the process, the board is pressed between rollers to reduce the fluctuation in the thickness of the board and to change some of the board's properties, such as smoothness and gloss. After calendering the board is reeled into large parent rolls. Finished parent rolls are taken to the winder, where they are cut into smaller rolls.

2.1 Board and its properties

Several types of board exist, and they can vary, for example, in number of layers, types of used pulps, coatings and in used additives. Changing these factors in a right way, the properties of the board can be tailored as desired. The type of wood from which the pulp is made affects the properties of board (Häggblom-Ahnger & Komulainen, 2006). The fibres of softwood and hardwood differ from each other in their dimensions, and this affects the strength- and optical properties, and formation of the board. Softwood pulp, which has longer fibres than hardwood pulp, can be used to produce stronger board than that from the hardwood pulp, whereas the hardwood pulp can improve the formation and opacity of the board and smoothen its surface. Pine and spruce are important softwood species used in papermaking, as well as the hardwood species birch and eucalyptus (Levlin, 1983).

According to Laamanen & Lahti (2008) paperboards can be classified into three main categories: carton boards, container boards and special boards. These can be further classified into more specific types of boards. For example, carton boards include such types as folding boxboard (FBB), solid bleached sulphate board (SBS) and solid unbleached sulphate board (SUB). Each of these three can also be used as baseboards in liquid packaging board (LPB), which can be coated with plastic or laminated with foil.

Low-density polyethylene acts as a barrier for water vapour and moisture, and it is commonly used in coating of LPB (Kuusipalo, et al., 2008). The board is coated with one layer of plastic on each side for packages of dairy products that have a short shelf life. In packages of products having long shelf life the board is laminated with aluminium foil, but a plastic coating on the liquid side of the packaging is still used. Virgin fibre is used for production of LPB since the products, such as milk or juice, contained in the packages made of LPB require high purity (Kiviranta, 2000).

Liquid packaging board is increasingly made using three layers, of which in the middle layer chemithermomechanical pulp (CTMP) can be utilized to have lower basis weight without affecting too much the board’s properties (Kuusipalo, et al., 2008). Several layers are used in LPB to give the package good stiffness, and it can be maximized by using pulp with high modulus of elasticity in outer layers and pulp having good bulk in the middle layer (Kiviranta, 2000). CTMP increases the bulk, and therefore it can be utilized in the middle layer. This is illustrated in Figure 2, in which an example of three-layer liquid packaging board structure is shown. Solid bleached sulphate board is often used in production of LPB (Kuusipalo, et al., 2008).

Figure 2. Example of three-layer liquid packaging board structure. Modified from (Kiviranta, 2000, p. 63).

2.2 Process chemicals and additives

To understand what kind of substances are likely to end up in the white water, i.e., the process water separated from the stock, it is useful to go through some of the basic chemicals and additives used in board manufacturing process. The chemicals and additives have two main purposes; to modify the properties of the board (functional additives), and to improve the functioning of the process itself (Häggblom-Ahnger & Komulainen, 2006). The chemistry of the wet end can become complex as the number of additives is increased, which can make the operation of the process more difficult. These substances can interact with each other and reduce their effectiveness. Therefore, it would be better to use only the necessary chemicals to minimize their number.

Fillers and coating pigments. In papermaking the fillers are normally white or almost white pigment powders used for filling the empty spaces between fibres, and they can be produced either synthetically or from natural minerals (Häggblom-Ahnger & Komulainen, 2006; Krogerus, 2007). In addition, organic pigments exist, but their prices are high and therefore they are rarely used as fillers (Häggblom-Ahnger & Komulainen, 2006). The coating pigments are additives similar to fillers, but they are a little finer grade and used with a little different intention (Krogerus, 2007). By using fillers, the characteristics of the product, such as surface smoothness, printability and gloss, can be improved while the costs of manufacturing the board will be reduced since the price of fillers is often lower compared to fibres. Fillers can be clays, talc, ground calcium carbonate (GCC) or precipitated calcium carbonate (PCC) amongst others. The properties of different minerals vary, which can be used to adjust the product properties as desired. A coated board can have a total mineral content of 5-20 %.

Dry-strength chemicals. These chemicals are used for binding the fibres and other raw materials together, strengthening the web (Häggblom-Ahnger & Komulainen, 2006; Krogerus, 2007). Among others, starch, vegetable gums, carboxymethylcellulose (CMC) and synthetic polymers are all used as dry-strength additives (Krogerus, 2007), of which the starch is the most common (Häggblom-Ahnger & Komulainen, 2006). The starch can attach to the fibres with hydrogen bonds, since it has several hydroxyl groups in its structure (Krogerus, 2007). The starch is also modified to improve its properties, and for example, cationic starch is often used in the Nordic countries. Starch content of board varies between 1-15 %.

Wet-strength chemicals. As the name suggests wet-strength chemicals are added to strengthen the board when it is wet (Häggblom-Ahnger & Komulainen, 2006). These chemicals help to keep the fibres together by creating bonds and preventing swelling of the fibres, further preventing the breakage of hydrogen bonds (Krogerus, 2007). Urea-formaldehyde, melamine-formaldehyde and polyaminoamide-epichlorohydrin are examples of synthetic polymers that can be used as wet-strength chemicals. The amount of urea-formaldehyde used varies between 0.8-2 % of the amount of fibre used, melamine-formaldehyde 0.5-2.5 % and polyamide-resin 0.2-1 % (Lipponen, 1983).

Sizing agents. The board has tendency to wet, but its hydrophobicity can be increased by sizing (Krogerus, 2007). The sizing agent can be applied on the surface of the board or internally, by mixing it in the papermaking furnish. Rosin sizes, which are made from natural rosins, can be used in acidic conditions (Häggblom-Ahnger & Komulainen, 2006). Neutral sizing agents, such as alkyl ketene dimer (AKD) and alkenyl succinic anhydride (ASA), are synthetic and can be used in neutral or alkaline conditions. Ketene dimers are used at amounts of 0.1-0.3 % of the used fibres (Lipponen, 1983).

Dyes and brighteners. To modify the appearance of the board, different dyes and optical brighteners might be used. According to Krogerus (2007) there are several types of dyes, including direct dyes, basic dyes, pigment dyes and acid dyes, and of these the direct dyes are the largest group. Suitability of a dye depends for instance on the end use and desired properties. Similar to dyes, the optical brightening agents (OBAs) are added in order to give the board a brighter appearance. In case of OBAs, for the board to appear brighter, UV-light is required to be present in the surrounding light since the UV-light is converted into blue light, which gives the brighter appearance. The amount of used OBAs is often between 0.1-0.5 % of the amount of pigment used in coating (Eiroma & Huuskonen, 1983).

Other additives. In addition to the already mentioned chemicals, there are several other functional chemicals used in papermaking. These include substances that improve grease repellence, reduce flammability, prevent growth of mould and fungi, and substances like preservatives (Häggblom-Ahnger & Komulainen, 2006), softeners, and coating colour additives, such as binders (Krogerus, 2007).

Process chemicals. These chemicals are intended to improve the operability of the process (Krogerus, 2007; Häggblom-Ahnger & Komulainen, 2006). One group of these chemicals is fixatives, which can remove anionic trash and dissolved and colloidal substances (DCS) from the process waters (Krogerus, 2007). Alum is an example of a commonly used fixative. Retention- and drainage polymers, adsorbents, dispersing- and pitch control agents, biocides, defoaming- and washing agents and pH adjusting agents are also process chemicals (Krogerus, 2007; Häggblom-Ahnger & Komulainen, 2006).

2.3 Board process water consumption

Board and paper processes, which are rather similar, consume a significant amount of water. For standard quality uncoated board machine a fresh water consumption of 3-12 m^3/t might be achieved if certain solutions for water reduction, such as reusing cooling waters and using clarified white water instead of fresh water, are utilized (Suhr, et al., 2015). For multi-ply folding boxboard produced from virgin fibres the fresh water consumption of 8-15 m^3/t could be achieved. According to the same study, the produced paper grades, nature of raw materials and the desired final quality all affect the consumption of water in the production process.

There are several reasons why the water consumption should be reduced. According to Weise et al. (2008) the legislation and permit conditions can have an effect on the water reduction, but also the costs of using water such as treating the fresh water and the generated effluents can encourage to use less water. In addition, if the availability of the fresh water is poor, more efficient use of fresh water is needed to compensate the lack of water. Reusing the same process waters can save thermal energy and raw materials, such as fibres.

If a board mill is closed mill, it does not produce waste water, but some water must be replaced because part of the water evaporates and some of the water is left in the moist rejects (Weise, et al., 2008). Depending on the design of the processes, this type of mill can encounter problems with the system stability and product quality. A sufficient water purification is needed in closed mill to ensure its operation. According to Stetter (2006b) a couple of mills have closed the circulations so that any effluents are not produced. These mills still consume fresh water at a volume rate of around 1.5 m^3/t paper.

Dahl (2008b) gives a good example how the reduction of water consumption affects the circulation water treatment in mechanical printing paper production: when the target for water consumption is 10–12 m^3/t, removing the solids from the water is the main concern, but with low consumptions of 4–8 m^3/t or 2–4 m^3/t additionally dissolved organic matter and salt concentrations need to be taken care of, respectively.

According to Stetter (2006b) the specific effluent volume rate of 3–5 m^3/t paper can be achieved in the production of board, but lower effluent volumes require additional purification of white water to avoid the occurrence of problems.

2.4 Water system of a board machine

The handling of the white water can vary significantly between mills, since equipment and tanks can be arranged in several different ways in the white water system (Panchapakesan, 1992). However, the aim of the white water system is to increase the reuse of white water and to reduce the amount of substances ending up in the effluent streams, which both help reducing the amount of needed raw materials such as fresh water and fibre.

The mills have different water circuits in which the process waters circulate (Stetter, 2006b). For efficient water usage the counter current principle is followed, which means that water flows backwards in the process; the fresh water is led to the paper machine and from its circulation the extra waters are led for use in previous stages, such as in stock preparation. The wastewater is then discharged from the beginning of the process. The stock should be transferred from each water circuit to next one in high consistency to reduce the amount of detrimental substances moving forward with the water.

Board- and paper machines have a short and long circulation. In short circulation the white water filtrated at the wire section is used again to dilute the thick stock which is led to the headbox (Weise, et al., 2008). Using the water again has the advantages of saving water and returning the raw materials back to use, but it has to be cleaned from impurities (Häggblom-Ahnger & Komulainen, 2006). The cleaning done in the short circulation often utilizes hydro cyclones and pressure screens for cleaning the stock, although the stock is cleaned also apart from the short circulation. Since the disturbances in the short circulation directly affect the final product, the short circulation can be considered as the most sensitive part of the papermaking.

The short circulation is demonstrated in Figure 3. The principle is described well in the work of Häggblom-Ahnger & Komulainen (2006): in short circulation the thick stock from machine chest is fed to the bottom of the wire pit, where it is diluted using the white water that has passed through the wire. From the wire pit the diluted stock is led to the first stage of centrifugal cleaning by using the stock fan pump. The accept from the first stage of centrifugal cleaning is then directed to the deaeration tank, where air is removed from the water. Next the headbox supply pump is used to pump the stock from the deaeration tank through pressure screens, but in cases where the deaeration tank does not exist, the stock fan pump can be used as the headbox supply pump. After the pressure screens the stock is led to the headbox and distributed on the wire. In case of multi-ply board, the manufacturing process gets more complicated, since one short circulation is needed for each layer of board.

Some chemicals and additives are also added in the short circulation, right before the stock fan pump and after the pressure screens (Weise, et al., 2008). These include the retention aid, which is fed to the pipe leading to headbox from the pressure screens. As the name suggests, retention aid improves the retention of the stock at the wire section, meaning that less of the solids pass through the wire with the white water (Häggblom-Ahnger & Komulainen, 2006).

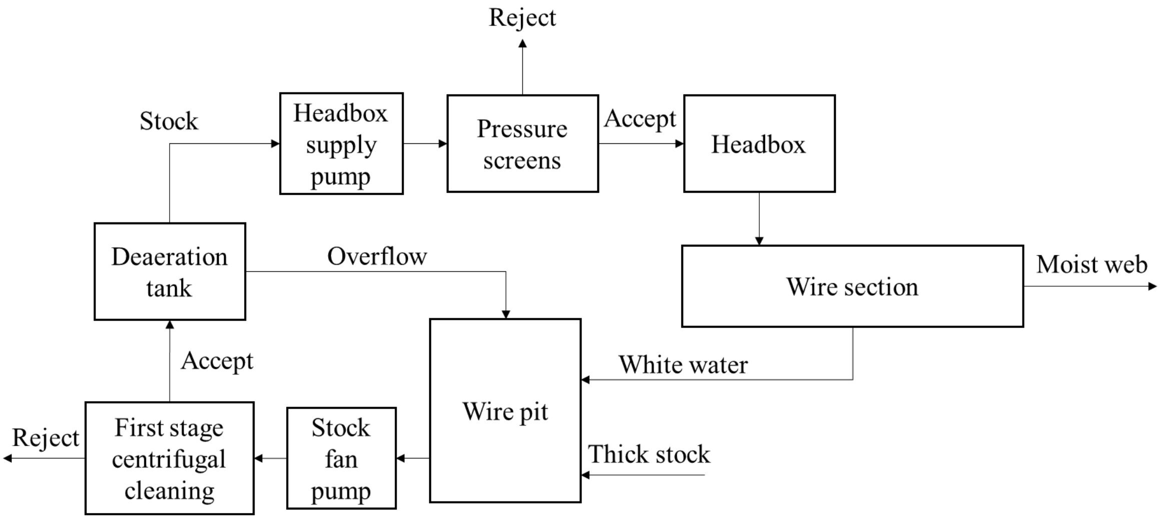

Figure 3. Description of short circulation. Based on (Weise, et al., 2008; Häggblom-Ahnger & Komulainen, 2006).

The short circulation is connected to the long circulation so that the extra white water that is not used in the short circulation is led to the long circulation (Weise, et al., 2008). In addition, other process waters are directed into the long circulation for reuse. Often fibres are recovered from the long circulation, and the waters are cleaned in order to use them again.

Example of the basic elements belonging to a water system of a board mill is presented in Figure 4. The white water that is not used in short circulation is led from the overflow of the wire pit into a circulation water tank (Häggblom-Ahnger & Komulainen, 2006). The white water from the tank is used in dilution of stock at stock preparation, but it is also led to the recovery of fibres at the disc filter. The cloudy filtrate from the disc filter is recycled back to the feed of the filter, and the clear filtrate is collected in a white water tower. The super clear filtrate is used as shower waters. The purified white water might be also used as vacuum system waters and cooling waters (Smook, 2016), as long as the purity requirements are met.

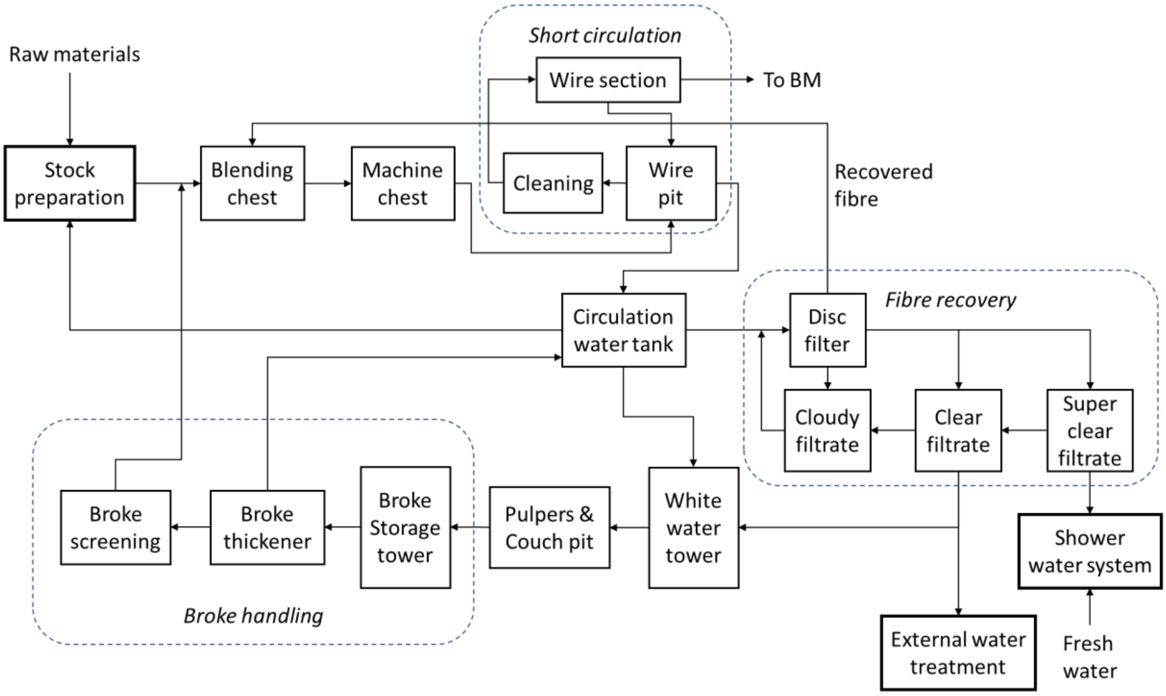

Figure 4. Example of processes included in the water system of a board mill at rough level. Modified from (Sundholm, 2008; Weise, et al., 2008; Häggblom-Ahnger & Komulainen, 2006).

There are a few sources from which the fresh water is introduced into the water system, including paper machine's showers, and chemical dilution- and make-up waters (Weise, et al., 2008). In case of an integrated mill, water is carried to the paper mill also mixed with the stock. In addition, the fresh water is used in high pressure sprays and sealing waters (Stetter, 2006b). The shower water is the water which is used for cleaning and lubricating the machine's fabrics and felts by using showers (Suhr, et al., 2015).

Usually, the fresh water is utilized in cooling before it is led to other process applications (Stetter, 2006b). At an integrated mill, the paper machine is the location to which main part of the fresh water is led (Weise, et al., 2008). When more process water is needed, warm fresh water can be added to the white water tank. Leading the warm fresh water to the white water tank has less effect to the consistencies and wet end chemistry since the location in the process is not near the headbox.

In addition to using steam, recovered heat from the hood of the paper machine can be used for heating the fresh water (Weise, et al., 2008). Suitable temperature for the stock is usually between 46 °C and 54 °C. Higher stock temperatures have the advantage of reducing microbial and fungal growth. Increasing the white water temperature to a certain extent has also the advantage of decreasing the viscosity and improving the drainage at the wire, but too high temperatures can cause the retention of fines, filler and size to decrease (Panchapakesan, 1992). The temperature of the stock on the wire can also be increased due to closing of the water system (Anon., 1991).

2.5 Broke system

In the manufacturing process of paper and board the generation of broke is unavoidable. The broke is any paper that is formed but which is discarded at the mill (Thomas, 1992; Weise, et al., 2008). The broke is used again at the machine by pulping, cleaning, and storing it first (Weise, et al., 2008). This is done in the broke system, which can be thought as a separate system or to be part of the stock preparation.

As with the paper machines, the broke system designs are different from mill to mill (Thomas, 1992). The broke system must respond quickly to the changing situations, as the amount of generated broke can vary significantly. Still the system has to return the pulp back to the process without having too much effect on the stock fed to the machine. Although sometimes done, integrating the broke system and white water saveall (the fibre recovery unit) is not recommended, since this can cause system instability because the broke is produced intermittently but white water is fed to the saveall constantly (Thomas, 1992; Weise, et al., 2008).

According to Weise et al. (2008) the main operations in broke handling are transportation of the broke, pulping, storage, cleaning and homogenizing, and dosage. For example, thickening, screening, and deflaking could be included in the treatment of broke, but the necessary steps are determined by the requirements of the machine (Stetter, 2006a). The broke is added back to the process in regulated amounts because the properties of the broke differ from those of fresh stock. When a web break occurs more of the broke is added to the stock that is led to the machine (Weise, et al., 2008). This can contribute to emergence of new breaks.

3 DIFFERENT WATER FRACTIONS AND THEIR QUALITY

Mills usually have different types of water for different purposes, and these types include mechanically treated water, chemically treated water, drinking water and water for fire-fighting, of which the last mentioned has often a pressure of 10-12 bars (Hynninen, 2008a). The drinking water and firefighting water is used in such applications as their name suggests, but the purposes of mechanically treated and chemically treated waters are not as obvious. The mechanically treated water is not as pure as the chemically treated water, and therefore the mechanically treated water can be used in applications where high quality water is not necessary. These applications can be, for example, cooling of equipment and use in water posts. The chemically treated water is used in applications where higher quality of water is required, such as in dilutions of chemicals.

According to Nilsen (1983) the sealing- and cooling waters are usually so clean after their use that it is useful to gather them to their own sewers. The waters from the sewers are led to separation of oil, from which the clean waters are discharged back to the environment. This will reduce the amount of effluents led to the water treatment. Often these clean waters are led to rainwater sewers, but the reuse of these waters could be worth consideration.

Mills also produce water fractions, such as the circulation waters and the effluents. Showers at the press section of a paper machine use the purest water, fresh water, which causes the used waters coming from the press section to be the most dilute of the machine’s waters (Häggblom-Ahnger & Komulainen, 2006). The white water from which the fibres are re-covered using disc filter, is often filtrated into cloudy-, clear- and super clear filtrates, of which the last two are reused in other applications and the first is circulated back to the disc filter.

3.1 Impurities in white water

There are numerous substances mixed in varying amounts in the white water of a board machine, and thus it is quite impossible to list every substance that can occur in the white water. The impurities in white water include dissolved and colloidal substances (DCS), sticky materials, pitch from wood extractives, white pitch from binders, dirt particles and inorganic ions (Alén & Selin, 2007). These come from several sources including the pulp, the process water used for transportation of the pulp to the mill (in integrated mills), broke, raw water, additives, and other used chemicals. The composition of white water is different at each machine, since there are differences in the construction of the machines, used raw materials, produced grades and production conditions. The substances in the white water can cause deposits, especially when the conditions are altered, for example, when the pH, charge or temperature is changed.

The impurities can be detrimental in different ways. For example, dissolved materials can precipitate on equipment surfaces, and since the waters contain nutrients, microbial activity can lead to formation of slime (Weise, et al., 2008). These can have negative effects on the manufacturing process and the product itself. The accumulation of dirt and slime can be avoided to some extent by using faster water flow speeds, smooth steel surfaces and suitable materials amongst other things that can be considered in the design of the process. In addition, microbial activity can lead to corrosion of the equipment.

The detrimental substances found in the white water can decrease the efficiency of other chemicals and be attached to the surfaces of solids in the water, such as fibres and fillers, which in turn can cause problems with the properties of the product, for example, bonding of the fibres (Weise, et al., 2008). Although, according to Nilsen (1983) only when the recycling rate is high enough the DCS in the white water start to stick to the product in significant amounts. Since there are large variety of substances in the mill process waters, chemical oxygen demand (COD) values can be used to give some kind of picture how much detrimental substances are present in the waters, in addition to more specific measurements (Weise, et al., 2008). Closing the water system leads to increase in the detrimental substances, and when less effluent is produced more of these substances can end up in the product (Stetter, 2006b). If no effluent is produced at all, the concentration of detrimental substances rises high, and additional technologies for purification of white water are needed.

There are number of ions dissolved in the process waters and they can affect negatively to the process and the product (Weise, et al., 2008). For example, corrosion of surfaces can be the consequence of too high concentration of chloride ions, and too high concentration of ions overall can affect the swelling of the fibres and further their properties. The precipitation of the salts is not only caused by the reactions between the ions, but also by changing conditions, such as temperature rise (Alén & Selin, 2007). Calcium sulphate is an example of this type of salt which precipitates as the temperature is raised, and one place where this might occur in the process is the refiner blades.

3.2 Treatment of board process waters

Purity of process waters in paper industry is of high importance, since the waters are in contact with the product and may contaminate it and influence its final quality. Therefore, the raw water, which is often taken from lakes and rivers, needs to be treated before its use in the process. The white water contains impurities that can come from different sources, including the pulp and the chemicals used in the board process, and using the water again in certain applications requires purification before its use. Also, the used process waters that are discharged as wastewater contain substances that need to be removed before they are released back to the environment in order to prevent pollution.

3.2.1 Raw water

According to Hynninen (2008a) raw water is usually made from surface waters of lakes or rivers, and the quality of water is dependent on the water source. The mills are designed differently and their requirements for water quality differ from each other. Water availability and local conditions affect to the selection of water source, and sometimes groundwater is used as the water source (Stetter, 2006b).

The raw waters have several impurities and properties that affect differently the board manufacturing process (Hynninen, 2008a). The water can be coloured by humus, copper, iron, or manganese compounds, which, if not treated properly, can lead to change in colour of the pulp. These impurities can vary in colours of brownish, yellowish, greenish, or greyish. Chlorides, carbon dioxide and oxygen are substances that may cause corrosion in specific conditions, and therefore may need to be treated. Other properties of the water that may need treatment include the cloudiness, hardness, alkalinity, odour, and taste of the water, depending on where the water is intended to be used.

Often the chemical treatment of the raw water is needed, although the solids can be removed mechanically (Hynninen, 2008a). To reduce the number of solid particles ending up in the raw water, the location for water intake should be such that the water flows slowly. Before the chemical treatment, a mechanical treatment is done using screens and filters. The water can be first filtered with a coarse screen to remove larger trashes, after which the water is filtered with a tighter screen.

In pulp and paper industry the chemical treatment of raw water starts usually from dosing of chemicals, but sometimes the process can start from aeration (Hynninen, 2008a). In Finland humus, iron and manganese can be present in waters, and a chemical precipitation for their removal is often needed. Oxidation of iron and manganese can be utilized in their removal, and this can be performed by using oxidising chemicals or aeration. After oxidation, chemicals are added and the mixture is stirred rapidly to cause the formation of micro-flocs, which will eventually stick together and grow in size later on when the mixture is stirred more slowly. The produced larger flocs are then removed from the water using sedimentation or flotation. In sedimentation the flocs are settled on the bottom of a clarifier, and in the flotation the flocs are gathered on the surface by using air bubbles mixed in the water. The clarification step removes most of the flocs, but still some of them are left in the water. Therefore, the water still needs to be filtrated. After filtration, the water can be disinfected, and it is ready for use.

3.2.2 White water

White water is the process water separated from the stock at the wet end of a board machine. It is important to have a stable quality of white water, because the variations in the quality can affect several parts of the process, such as stock proportioning, dewatering, and control of consistency of the stock fed to the machine (Panchapakesan, 1992).

The quality requirements for water reuse affects the selection of mill's internal water treatment methods (Nuortila-Jokinen, 1995). The components which need separation must be known, because in some cases only suspended solids need to be removed and sometimes removal of colloids might be needed, for example. The internal water treatment can be accomplished by using mechanical separation, chemical precipitation and flotation, biological treatment, evaporation, and membrane filtration.

White water contains fibres and suspended solids, which can be recovered using different technologies. The fibre recovery unit is often called saveall, and one of the most used equipment in this task is the disc filter (Weise, et al., 2008). When disc filter is used to recover the fibres, additional pulp, known as sweetener, is fed to the white water inflow of the disc filter. This is done because a sufficient filter cake must be formed so that the disc filter can operate correctly. Preferably long fibre chemical softwood pulp is used as sweetener. As the cake layer thickens during the filtration, less solids go through the filter cake and a clearer solution is produced. Therefore, by separating the filtrates from different phases of filtration, cloudy-, clear-, and super clear filtrates can be formed. Flotation, sedimentation, and other types of filtration could be also used to separate the solids from the water. When there is a small amount of fillers in the water, filtration suits well for the water purification, whereas for waters having higher content of fillers sedimentation is a suitable method (Nilsen, 1983). Disc filters have the advantages of taking only little space compared to their capacity, they produce higher quality filtrates, tolerate small changes in volume and concentration of feed and also system disturbances to some extent (Panchapakesan, 1992).

The clear- and super clear filtrates can be used again in the process when the quality requirements are met. Pulp dilution and make-up water for stock preparation are applications where the clear filtrate is sometimes used (Weise, et al., 2008). The excess filtrate is discharged from the clear filtrate tank into a sewer by controlling its flow, for example, based on the filtrate level. The super clear filtrate can be used for showers and corresponding applications. Quality requirements for shower water are presented in Table I (Weise, et al., 2008, p. 202) which shows that the solids content has to be quite low in the shower water, and when the content gets higher also the orifice of the shower should be larger. In addition to this, the used water should not contain detrimental substances that could precipitate and plug the showers (Weise, et al., 2008). According to Panchapakesan (1992) the cloudy filtrate could be used also in the wet end dilutions and in the pulpers.

Table I. Quality requirements for shower water. (Weise, et al., 2008, p. 202)

Solids content	Possible application for shower water
< 50 ppm	Equivalent to filtered fresh water
50-75 ppm	Usable in ≥ 1 mm orifice
75-100 ppm	Usable in ≥ 1.5 mm orifice
100-200 ppm	Usable in ≥ 3 mm orifice
200-500 ppm	Brush type shower recommended
> 500 ppm	Purgable shower recommended

Dissolved air flotation (DAF), also called microflotation, can be used in the treatment of process water (Weise, et al., 2008). In older machines this technology is used in savealls, and it is suitable for removing ash and fines (Stetter, 2006b). Chemicals are often used to improve the treatment (Weise, et al., 2008). With the help of chemicals usually 10-40 % of colloidal material and 85-98 % of microscopic and fine materials can be removed. In DAF the air is compressed typically at pressures of 500-700 kPa to dissolve it into water in an air saturation reactor. When the pressure is released, small air bubbles (40-100 µm) are formed. The fine particles in the water are raised to the surface of the flotation tank with the help of the raising air bubbles, and the heavier particles sink to the bottom, from which they are removed. In addition to process water treatment, DAF is also used in fresh water and effluent treatments.

To ensure that the quality requirements concerning the suspended solids are met, the white water can be purified just before using it in some application, and one way to do this is using curved or flat screens (Nilsen, 1983). Too high solids content in the water can cause for example plugging of the shower nozzles, wires, and felts, and also corrosion and scaling can occur (Panchapakesan, 1992).

Although the white water is clarified in saveall disc filter, the clarified filtrate still has organic and inorganic substances (Nuortila-Jokinen, 1995). If dissolved and colloidal organics need to be removed from water, ultrafiltration, anaerobic biological treatment, and evaporation could be utilized. In case of inorganic salts, nanofiltration and evaporation could be used as separation method. Besides the purification methods, retention plays also an important role in the white water purity, since cleaner white water is formed when more of the components stick to the paper web.

3.2.3 Wastewater

The chemical composition of wastewater in pulp and paper industry varies greatly and it is still partly unknown, but by using the measurements of chemical oxygen demand (COD), biological oxygen demand (BOD) and adsorbable organic halogens (AOX), the impact of releasing the wastewater in the environment can be estimated to a certain extent (Hynninen, 2008b). In addition, many other measurements, such as amount of suspended solids and nutrients are also used to evaluate the quality of the wastewater. In Table II indicative levels of different discharges from paper and board manufacturing processes are presented. As the Table II shows, there is significant variation in the amount of effluent between different paper grades. Also, some variation between the effluent loads exists, especially the amount of nitrogen seems to vary greatly. According to Hynninen (2008b) the raw materials, additives, used technologies and conditions all affect the amount of discharges.

Table II. Indicative discharge levels from paper and board manufacturing for various paper grades. (Hynninen, 2008b, p. 89)

Product	Effluent, m^3/t	Suspended solids, kg/t	BOD, kg/t	COD, kg/t	N, g/t	P, g/t
Fine paper, coated	30-50	10-20	3-8	10-20	50-100	5
Newsprint	10-25	5-10	1-3	2-4	10-20	5
Folding boxboard	10-25	5-10	2-4	3-6	50-100	8
Sack paper	15-30	5-10	2-4	4-8	100-200	15
Tissue	20-40	5-10	1-3	3-6	50-80	8

The effluents produced at a mill are often treated externally (Hynninen, 2008b). This has the advantage that it does not affect the production process of board. The effluent treatment can be done using physical, physical-chemical, and biological methods. The devices used in treatment of effluents work basically in the same manner as the devices used in purification of white water (Nilsen, 1983). In general, the external treatment is carried out in primary and secondary treatments (Smook, 2016). The first one removes suspended solids, and it can be done via sedimentation. The latter treatment is biological, and it reduces the BOD. Because the effluent streams may need different treatments, they are directed in a way that they go only through the necessary treatments. Since the micro-organisms prefer temperatures of 25-35 °C, the effluents may need cooling before letting them into the biological treatment step.

3.3 Vacuum pump-, sealing- and cooling waters

The vacuum pumps in paper industry can be classified into two categories, volumetric pumps, and turbo blowers (Honkamaa, 2008). In the first category, the most common pump is the liquid ring pump, which creates a ring of water inside the pump by utilizing centrifugal forces. Compressing the air produces heat which is removed from the pump by the working water, also known as sealing water. Water is consumed by the pump, since part of this sealing water, is removed with the air from the pump and it must be compensated. According to Panchapakesan (1992) liquid ring pumps use great amounts of seal water. The turbo blowers have the benefit of not needing sealing water, but no water or other particles should be contained in the incoming air (Honkamaa, 2008). In case of low vacuum applications, single-stage blowers might be utilized.

To reduce the consumption of vacuum pump sealing water, the waters could be recirculated (Panchapakesan, 1992). Because of the high temperature of water exiting the pump, the water needs to be cooled when recirculation is used. High water temperature can weaken the vacuum created (Panchapakesan, 1992), and increase corrosion and surface damage (Honkamaa, 2008). The temperature can be controlled by feeding cool fresh water to the circulation and removing the used hot water (Honkamaa, 2008). Additionally, a cooling tower can be included in the circulation. The vacuum pumps can also be arranged in a cascade, so that the cool water is fed to high vacuum pumps and their warm outflow is fed to the inlet of low vacuum pumps, from which hot outflow is then discharged or used elsewhere (Honkamaa, 2008; Panchapakesan, 1992). This can reduce the water use in the pumps by 50 %.

Around 10-15 % of the recirculated sealing water needs to be replaced by fresh water, which can reduce the accumulation of suspended material (Honkamaa, 2008; Panchapakesan, 1992). The fresh water used in the vacuum pumps has some quality requirements, and one example of recommended water properties for liquid ring pump is presented in Table III (Honkamaa, 2008, p. 502). As the table suggests, the sealing water should be quite clean and have a low temperature. In addition, low pH is not recommended, since it can cause corrosion (Panchapakesan, 1992).

Table III. Sealing water properties recommended for use in cast-iron liquid ring pump. (Honkamaa, 2008, p. 502)

Temperature	< 20 ℃ – 30 ℃
pH	> 7.0
Conductivity	< 2000 µS/cm
Cl^-	< 200 ppm
SO_4^-	< 200 ppm
Dissolved substances	< 1000 mg/L
Ca-hardness	< 200 ppm/$CaCO_3$ ekv.
Abrasive substances Ø > 10 µm	< 40–50 ppm

4 REDUCTION OF BOARD MACHINE WATER USAGE

The water consumption of board machine can be reduced in different ways. According to Dahl (2008b), pulp and water balances need to be formed to understand how the effluent loads coming from a board mill could be reduced. There are several possible options where the water usage can be improved. These include, for example, reuse of sealing waters, recycling vacuum pump waters, cooling of waters, and decreasing the number of places where process waters are led out. Closing the white water system effects positively to chemical consumption, loss of fibre, fines and fillers, white water heating costs, and environmental compliance (Panchapakesan, 1992).

When possible, fresh water should be replaced with white water, purified white water, or with pressurized air in applications which use fresh water (Nilsen, 1983). When solid impurities need to be removed from the water, filtration or clarification can be utilized, but if also removal of DCS is required then other purification methods are needed. These include, for instance, chemical precipitation, membrane technology, and activated carbon adsorption. If the replacement of fresh water is not possible, the fresh water consumption could be reduced by adjusting pressure of water or by changing the properties or the location of the device using the fresh water.

In work of Suhr et al. (2015) suggestions for water reduction were presented. Shower water system consumes most of the fresh water, and therefore by replacing fresh water of the showers with clarified white water, the fresh water consumption can be reduced. It was also noted that the colloidal material in the white water might precipitate on the press section felts and cause clogging. Thus, saveall filtrates should not be used in the press section showers unless they are treated with suitable method. In addition, the technical solutions are not the only way to reduce the water consumption: improving the production planning, and training and motivating the staff were also suggested for reducing the water consumption.

5 STORA ENSO INTEGRATED MILL

Stora Enso's largest integrated mill, Imatra mills, is also the largest board producer in Finland (Stora Enso, 2021a). The mills consist of two units, Kaukopää and Tainionkoski. There are four board machines of which three are located in Kaukopää, including the board machine four. In addition, there is one paper machine and four coating machines at the Imatra mills. The mills use their own pulp and chemithermomechanical pulp to produce liquid packaging-, food- and graphical boards. Around 1.1 million metric tons of board and paper is produced annually at the mills (Stora Enso, 2021d). This work focuses only on BM4, because the work was conducted there.

The BM4 produces liquid packaging board, tray board and cupstock (Stora Enso, 2021b). The produced liquid packaging board is often coated with polyethylene plastic, and it has applications for example in milk-, juice-, detergent-, and wine packaging (Stora Enso, 2021c). The board produced at BM4 has three layers, and it is made from bleached sulphate pulp and CTMP. The produced board is 6.3 m wide, and its production capacity is 375 000 t/a (Stora Enso, 2021d).

At the wire section of BM4 there is one wire and headbox for each layer of board, and in addition a former on top of the middle layer wire. All three layers have their own short circulations. The wire section is followed by the press section, which consists of three presses, after which the board enters the drying section. Drying is followed by calendering, which is done using two different types of calenders. After calendering the board is reeled and taken to the winder.

EXPERIMENTAL PART

6 AIM OF THE EXPERIMENTAL PART

In the experimental part of this work there were two main aims; to map the water streams of different water fractions at BM4, and to investigate the possibility to reduce the water consumption. The information of this part is based on piping and instrumentation diagrams (P&ID), Valmet DNA automation system (Valmet, 2021a), observations, discussions with the Stora Enso's personnel, and information found on the company's intranet and internal systems.

After researching the water system of the BM4 from P&IDs, related documents, and DNA automation system, conversations with the company's personnel were held to better understand where the water consumption could potentially be reduced. The filtrate water filter was eventually selected as a subject of study. The filter is used for removing fibres from the super clear filtrate of a disc filter, which is used for thickening of dilute broke. The filtrate water filter is needed, because the super clear filtrate is led to shower water tank, and the shower water should not contain particles that could block shower nozzles. The flow through the filtrate water filter is restricted by an automatic valve to 16 % opening, since previously higher flows have caused clogging of the filter. The aim was to study if the flow of super clear filtrate to the shower water tank could be increased by opening the valve more without clogging the filter, and to study its effects to the solids content of shower water tank water. In order to study this, a test run was conducted at the BM4. Increasing the share of super clear filtrate in the shower water tank would allow to reduce the use of warm fresh water, since the shower water tank takes part of its water from the warm water tank. The part of the process involved in the test run is presented as simplified process diagram in Figure 5.

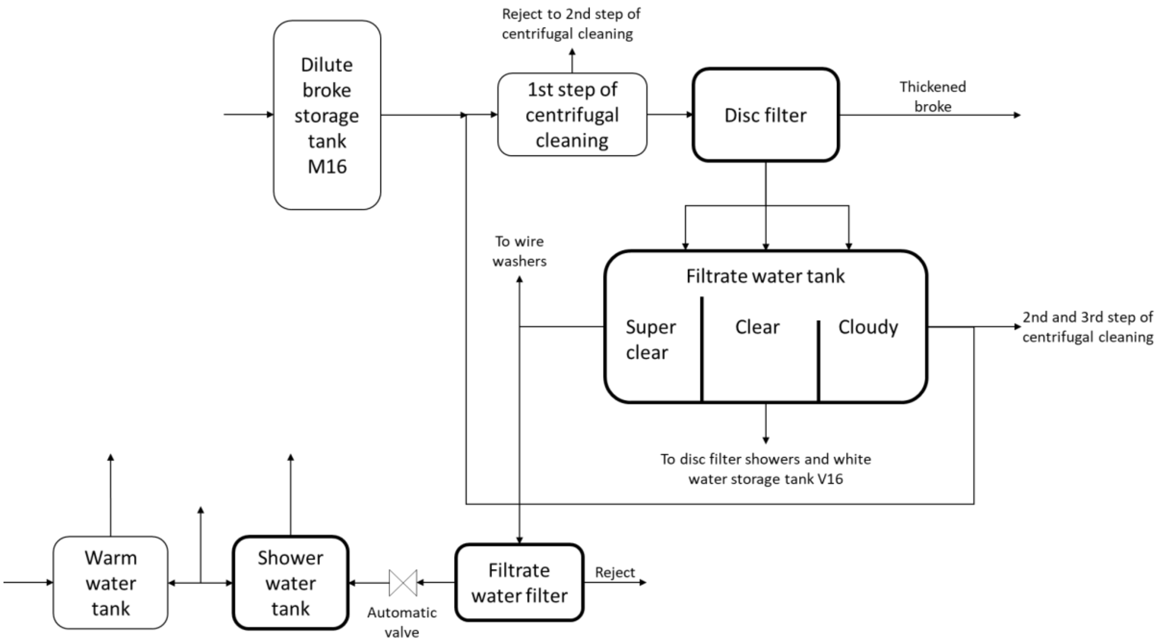

Figure 5. Simplified process diagram of the equipment related to the test run. Only the essential streams are shown. Other valves than the automatic valve which was studied are not shown to keep the diagram clear.

7 DIFFERENT WATER FRACTIONS AND THEIR USE AT BM4

There are several water fractions that are used at BM4. These include raw water, chemically purified waters from raw water treatment plant and precipitation plant, cooling water, sealing water and white water. There is also firefighting water, in which raw water is used. Warm water from evaporating plant is used in dilution of CTMP pulp at the bottom of a CTMP tank. In addition, small amounts of steam condensates are utilized in applications where warm high-quality water is needed, such as in trim showers, moisturizers and smoothing press roll washer. These water fractions differ from each other in terms of quality and temperature.

Raw water is led to the board mill from lake Saimaa (Stora Enso, 2015a). It is pumped from raw water pumping station, where the water is cleaned mechanically with screens and disinfected using chlorine dioxide. The pumping station provides raw water also to other sites at the mill. In addition, cooling water is pumped from the same pumping station to several locations at the mill, including BM4, although cooling water is also separately pumped to BM4 from another source. The raw water pumping station contains also the pumps for the firefighting water. Raw water is used at BM4 in different applications where high-quality water is not required. These include cooling of hydraulic units and gears, and certain washing applications, such as some of the water posts.

Chemically purified water is produced from the before mentioned raw water at two different locations, the raw water treatment plant and the precipitation plant (Stora Enso, 2020; Stora Enso, 2015b). These water treatment processes are quite similar. In both the raw water is heated, its pH is adjusted, chemicals are added to precipitate the impurities, the water is clarified and filtered using sand filters. The objectives for iron content and consumption of potassium permanganate of the water are slightly tighter at the precipitation plant. At BM4 the chemically purified water is used in applications where high-quality water is needed and the water could be in contact with the product, for example, in dilution of chemicals.

The sealing water used at BM4 is produced also from the raw water by using sand filtration, which improves the quality of water. This water fraction is produced at the board mill's filler- and additive department. As the name suggests it is used as sealing water in different process equipment, for example in some of the refiners and pumps at the board machine.

Cooling water, needed to be colder than raw water, is pumped from a basin of the lake. As it was mentioned, there are two sources for cooling water that is used at BM4. The water which is used in larger part of the cooling applications, is pumped directly to the BM4, and the pumps for this water are located in the lower basement of the board machine. The other cooling water is pumped from raw water pumping station. Both waters have similar cooling applications. The most common of them is the air conditioning at BM4. Some hydraulic power units use this water fraction for cooling, but most of them are cooled by using the raw water.

The white water, which is the process water that is produced in the board manufacturing, is gathered in storage tank, and used again in the process. At BM4 white water is used, for example, in adjusting the level of the wire pits, the dilutions of the stock in different parts of the process, and flushing of certain lines.

8 CONSUMPTION OF DIFFERENT WATER FRACTIONS AT BM4

The consumption of different water fractions at BM4 was investigated by using the data collected by flow meters. The flow meters are in the pipelines in such locations that the total consumption of each water fraction at BM4 can be measured. The flow rate data for the different water fractions were obtained from the Wedge process analysis system (Trimble Inc., 2021), by using the flow meters' tag numbers which were found from the DNA automation system. Therefore, the first step in the experimental part was to examine the total consumptions of each water fraction.

The existing flow rate data from Wedge, which was measured once a minute from each pipeline by existing online flow meters, was collected from time interval 1.1.2020–1.1.2021. The flow meters are located quite close to the beginning of the pipelines at BM4, so that the water is distributed to several locations afterwards. The examination included flow rates of five different water fractions (named as water fractions 1-5), and it was done by using the data from production of three different board grades. All five water fractions were fresh water and they differed from each other in their purity and temperature. Uses of the first four water fractions are discussed in more detail in the next chapter. The three selected board grades were the main grades with the most frequently produced grammages, which are presented in Table IV.

Table IV. Grammages of the board grades used in examination of the consumptions of the five different water fractions.

Grade	Grade 1	Grade 2	Grade 3
Grammage, g/m^2	310	265	257

First, the longer breaks in the BM4 production (approximately over nine hours), and clear outliers were removed from the data in the Wedge process analysis system, to obtain values that would better represent the normal production. Although this reduced the deviation in the data, the average flow rate values were mainly affected only a little. Also, the water fractions 1 and 4 had significantly high deviation, which means that comparison of their average values between the three grades is not very accurate. The average flow rate values of these two water fractions also had the greatest differences, although the greatest difference was only 2.2 % between the grade 1 and grade 3 in water fraction 1 flow rate. The difference could be also explained by the high deviation.

Since the consumption of different water fractions was very similar between the selected grades, average values between all three grades were calculated. The average consumption of each water fraction is presented as its share of the total water consumption of the five water fractions in Figure 6. The water fraction 4 is also used at coating machine PE2 and therefore its flow rate measurements do not represent only the consumption at BM4.

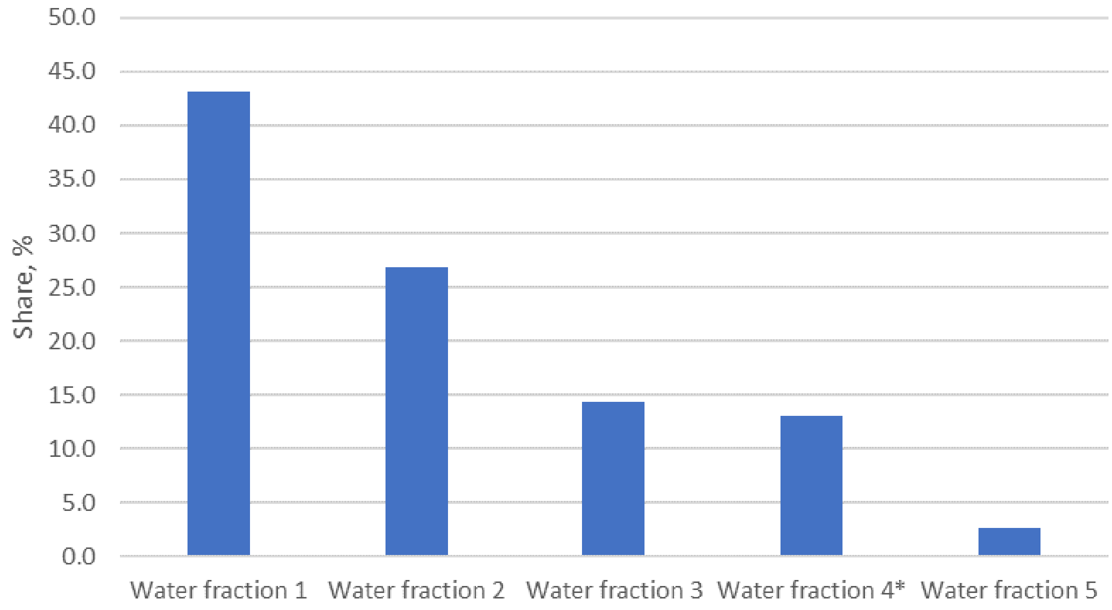

Figure 6. Share of each water fraction in the total consumption of the examined water fractions at BM4. * = Water fraction partly used at coating machine PE2.

The Figure 6 shows that water fraction 1 is clearly the most used fraction having a share of around 43 % of total consumption of these five water fractions. Since the water fraction 5 consumption is very low compared to other water fractions, it is left out of the further examination of the applications consuming water.

9 MAPPING OF WATER STREAMS

The mapping of the water streams provides information on the applications that consume the different water fractions at BM4. This information can be then used, for example, for searching new possibilities for the reduction of water consumption.

The mapping was done by gathering all found water consumers of selected water fractions into a spreadsheet, which was a very time-consuming task. This was done by going through numerous piping and instrumentation diagrams and all the process diagrams of BM4 in the DNA automation system line by line. The pipelines were also followed at the site for large part of the applications, especially for uncertain ones, to see how the pipelines were actually connected, although certain pipelines could not be followed from the floor level. The functional descriptions of several devices, such as pumps, motors and valves were utilized in order to understand for which purpose the water fractions were used at each application. Information of various devices were also searched from the company's enterprise resource planning system (ERP) to find out the purpose for water use. In addition, discussions were held with the company's personnel to get to know the purposes which could not be solved by using the above-mentioned information.

Since there exists a very high number of pipelines at the site, only four of the five water fractions that were examined previously in this work and which had the highest total consumptions, were included in the mapping. The fifth water stream is used in several locations, but its consumption is very low compared to the other water fractions. The outcome from the mapping was a spreadsheet, which contained the application, the purpose of the water use, average consumption from online flow meters (if existed) from period 1.1.2020–1.1.2021, and notes on each row. The number of found applications were 95 and since including the whole table in this work as such would not provide much useful additional information, only a summary of the table is presented in this work. In Table V the number of applications is presented for various purposes for each examined water fraction. The actual number of devices using the water is little higher than the number of the listed applications, because in some cases one application includes several devices. Also, some applications have two purposes for their water use, for example, a liquid ring vacuum pump can use the same water fraction for its water ring and cooling. Certain applications listed in the original table were not in use at study period, so they were excluded from the Table V. Therefore, the total number of applications in the table does not equal to 95. In Table V the water fraction 4 comes from two different sources and the number of applications is therefore presented in two parts. The first number represents the water fraction 4 which is pumped directly to BM4 and the second number represents water originating from raw water pumping station.

Table V. Number of individual applications for different purposes of the examined water fractions at BM4.

	Water fraction 1	Water fraction 2	Water fraction 3	Water fraction 4
Cooling	35	1	0	12 + 7
Water intake	1	4	1	0 + 0
Water- or water level securing	12	3	0	1 + 0
Rinsing or washing	4	3	0	0 + 0
Sealing and water rings	6	0	0	0 + 0
Other	2	0	1	1 + 0
Total	60	11	2	21

In Table V the *water intake* includes the applications that take water (mainly into a tank) during normal operation of the board machine, and the *water- or water level securing* includes the applications that use water only in exceptional situations, such as during breaks at the board machine or at the machine start-ups to secure the water supply. It was difficult to categorize some of the applications, but most of the applications could be categorized under cooling, water intake, water- or water level securing, rinsing or washing, or sealing and water rings. Reduction of foam in tank by using water is an example which did not suit to any of the mentioned categories.

As the Table V shows, at BM4 the water fraction 1 is clearly the most widely used water fraction, since it has the highest number of applications consuming it. This is logical, since previously in this work it was discovered that water fraction 1 has also the highest consumption (see Figure 6). Water fraction 4 has the second highest number of applications, and both the water fraction 1 and 4 have most of their applications categorized under cooling. By comparing the number of applications in cooling to the total number of applications in the Table V, it follows that around 59 % of the listed applications use the water for cooling, which makes it the most common purpose for water use at BM4.

The Table V reveals also that many of the applications have a water- or water level securing, which is not constantly used. The water level securing is used for example when the water level in some tank decreases below a certain limit. The water securings exist for cases where the original water source would not be available, or the water flow would not be sufficient. For these reasons, some of these applications are very rarely used.

Water fractions 1 and 2 are used for rinsing and washing in a few individual applications. These include for example the use of some water posts and rinsing of certain pipelines. The water fraction 1 is also used in the water rings of certain vacuum pumps. In practice the water fraction 3 seems to be used only in one location at BM4 for the intake of water. The water fraction 3 has another application listed, which is a joint in a pipe that is likely used for sampling, but its consumption is insignificant compared to the total use of the water fraction.

In the beginning of the mapping it was decided that also the water consumption data from each mapped application having an online flow meter in its pipeline would be gathered from the Wedge, and the average consumption from a time interval of 1.1.2020–1.1.2021 would be calculated. As the mapping progressed, it was discovered that there are only a few flow meters, which mainly measure the total water flow to multiple applications. Only three online flow meters were found for individual applications that used purely water fraction 2. Other measurements either included several applications or multiple water fractions. In order to monitor the consumption in individual applications or in a small group of applications, installation of new online flow meters would be required. This is worth investing only in case the costs of investments and maintenance of new flow meters are smaller than the benefits achieved from more accurate monitoring of water consumption. Places where having a flow meter could be beneficial, would be the overflow pipes of certain tanks, which were also noted in the investigation report of Pöyry (2014). The flow meters would allow to monitor how often and in which quantity the overflows occur. The data would help to improve the water system and reduce the overflows. To find the equipment with the highest consumption in each water fraction currently, the original list of the mapped applications should be read through and flow meters would need to be installed to suitable locations to measure the consumption of each application. The consumption should then be observed for some period to get a representative average consumption.

It was noticed during the mapping that often the sealing- and cooling waters which were once used in some application, were led to sewers after their use. As it was mentioned in the literature part of this work, it should be considered if some of these waters can be led to the process. Thermal energy might be saved when the once used cooling waters are utilized again as process waters, since the cooling waters get warmer during their use and the process waters need to be warm. To save thermal energy, after their use the cooling waters should be at least as warm as the fresh water led to the process. The possibility for reuse would need to be examined separately for each cooling application.

Another observation during the mapping was that there are liquid ring vacuum pumps, which consume water for their water rings. In the literature part it was stated that liquid ring pumps require sealing water, but turbo blowers do not. Therefore, the liquid ring pumps could be replaced by turbo blowers in order to reduce the water consumption of BM4. Another way, which was also discussed in the literature part, would be to reduce the water consumption by recirculating the sealing waters of the liquid ring pumps, although this would not reduce the consumption to the same extent as changing the pump type to turbo blower.

During the mapping of the water streams, it was noticed that although the DNA automation system contained names for many of the equipment, it did not contain the position numbers (functional locations) for all of them, such as some tanks and hydraulic units. The numbers help to find additional information about the equipment from the company's internal systems, and also to locate the equipment at the site. Therefore, it would be useful in future to add this information into the DNA. It was also noticed that some individual water streams are named differently in DNA and P&ID's, which can be confusing. The only way to solve the correct water fraction was to go to the site and examine how the piping was installed. One thing that would facilitate finding correct pipelines would be to label the pipelines with their numbers, which can be found from the P&ID's. Currently there are some labels which reveal the flowing substance, but accurate labels would be even more useful.

The original table containing the applications for water use has more specific information about the equipment and it can be used at the mill for examining new water reduction possibilities. For example, each application could be gone through and examined whether another water fraction could be used instead, or if possibly produced waste waters could be led into the process or to clean water sewers instead of wastewater sewers, if not already. It would also require studying if it is feasible to make changes to the equipment and their piping, since the expenses from new installations might become greater than the achieved savings.

10 REDUCTION OF WARM WATER USE BY UTILIZING SUPER CLEAR FILTRATE

The aim at BM4 is to use as high volumes of the disc filter's super clear filtrate in the shower water tank as possible. This is because currently part of the shower water tank's water is taken from warm water tank, to which the fresh water is also added. Therefore, using more of the super clear filtrate in the shower water tank would reduce the consumption of fresh water and improve the utilization of already warm process water (see Figure 5).

At BM4 a disc filter is used for thickening of wet broke. The wet broke is fed to first step of centrifugal cleaning where it is cleaned from impurities and from which the accept is led to the disc filter. No sweetener is added to the feed of the disc filter. The filter type is Centerdisc CDI from GL&V, and it has 10 discs that have a diameter of 4000 mm. During the operation the filter applies vacuum formed in the drop legs of the filtrates to form the cake layer on the discs. The disc filter produces cloudy-, clear- and super clear filtrates, which are collected in a filtrate water tank. According to Pöyry (2014) the shares of the produced filtrates have been 17 % for super clear filtrate, 53 % for clear filtrate and 30 % for cloudy filtrate.

The filtrate water tank is divided in three separate sections so that each filtrate has its own section. The filtrate water tank is designed in a way that when the super clear filtrate section is filled full, it overflows into the clear filtrate section, which has similar overflow to the cloudy filtrate section. This is done using walls of different heights between the filtrate sections, and it prevents the mixing of super clear filtrate with the less clear filtrates. The cloudy filtrate section has overflow to the wastewater drain, which means that whenever overflow occurs some fibres, which are the raw material, are lost into the drain and therefore these situations should be avoided. In order to prevent the cloudy filtrate overflow to the drain, the clear filtrate overflow to the cloudy filtrate section is decreased by reducing the water level in the clear filtrate section. This is implemented by using an automatic valve which adjusts its opening based on the water level of the filtrate water tank and allows some of the clear filtrate pass to the drain. This is in line with the literature part, in which it was mentioned that the excess filtrate is discharged into the sewer from clear filtrate tank.

From the super clear filtrate section of the tank the filtrate is pumped through a filtrate water filter into the shower water tank. The water in the shower water tank should be clean, since solids, especially fibres, can plug the shower nozzles. Therefore, larger particles that might exist in the super clear filtrate are removed using the filtrate water filter before the super clear filtrate is led to the shower water tank.

The filtrate water filter is BOLLFILTER Automatic type 6.18 from BOLL & KIRCH, and its filtration grade is 150 µm. The filter has 40 longitudinal wedge wire candles, through which the liquid is filtered. The filter is designed for flow of 130 L/s, but it is currently restricted by an automatic valve, and therefore it is presumably lower. The required minimum pressure after the filter is 2 bar. The filter washes itself periodically by backwashing and removes the accumulated reject. The washing is also set to start automatically when the pressure difference of the filter raises above 60 kPa. The washing time and time between the washes can be changed from the DNA automation system.

After the filter outlet there is an automatic valve which can be controlled through the DNA. The valve restricts the flow through the filter, and the valve position is currently limited to 16 % of its maximum opening, because previously if the valve was opened too much and therefore the flow was increased, the filter started clogging. Based on the data from Wedge process analysis system, the valve has been mainly in that position a few years during the time the valve has been open. To be able to utilize more of the super clear filtrate, the valve must be opened more. Therefore, it needs to be examined how much the valve can be opened until clogging of the filter starts to occur. Also, the effects to the solids content of the shower water needs to be examined when the flow of super clear filtrate is increased.

The structure of the BOLLFILTER Automatic type 6.18 filter is shown in Figure 7. According to the filter's brochure (BOLL & KIRCH Filterbau GmbH, 2021), during filtration the fluid enters the filter through the inlet flange (3). Around half of the fluid flows into the open bottom ends of the filter candles (6) and half through the central riser pipe (4) to the top and into the upper open ends of the filter candles (5). The filter candles have gaps, through which the fluid is filtrated (7). During the backflushing phase, the flushing arm (1) and the covering arm (2) are rotated over the lower and upper ends of filter candles and the candles are washed (8) in turns using the filtrated fluid without stopping the filtration process. Simultaneously the sludge release valve is opened, and the reject is removed from the filter. The pressure difference is measured (9) from the inlet and outlet of the filter.

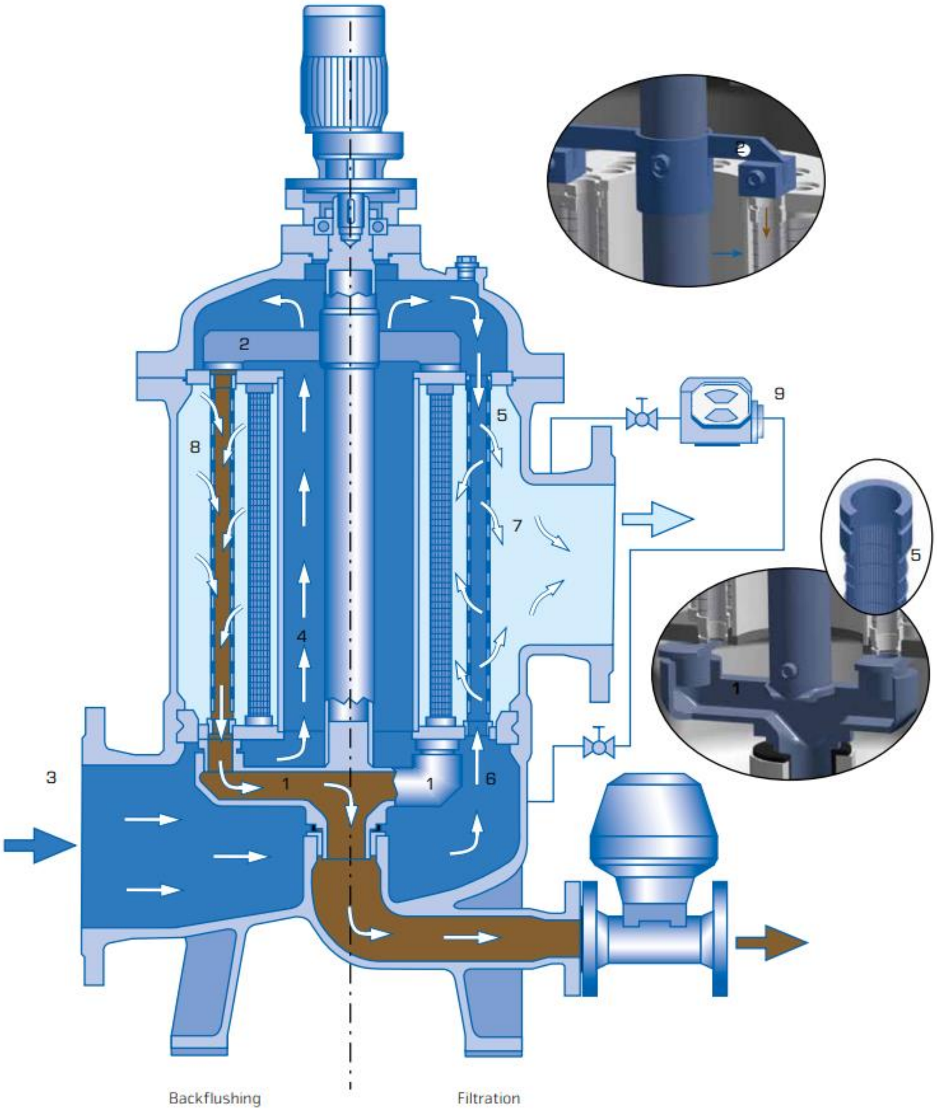

Figure 7. Structure of the BOLLFILTER Automatic type 6.18 which is used as the filtrate water filter at the BM4. Diagram from (BOLL & KIRCH Filterbau GmbH, 2021).

A test run was planned to examine if the valve could be opened more without clogging the filtrate water filter. First, the consistencies of wire waters were examined using data from Wedge, to see if there are significant differences in consistencies between board grades. This was done, because the wire water consistencies could give information about the amount of solids that can end up in the process waters. It was assumed that with higher consistencies also the solids content of process waters would be higher. The consistencies of top-, middle- and bottom layer wire waters were compared between seven board grades. The consistencies of middle layer wire waters on different board grades are presented in Figure 8. The consistency differences were the clearest in middle layer wire waters and the values were also higher than in top- and bottom layer wire waters. The already existing consistency data was taken from Wedge, from period 1.1.2020–31.12.2020, and it was not cleaned from outliers since a rough level estimation was sufficient and removing the outliers would not have affected the average values too considerably. Also, the deviation in the data was somewhat high, and therefore an accurate comparison of the values is not useful.

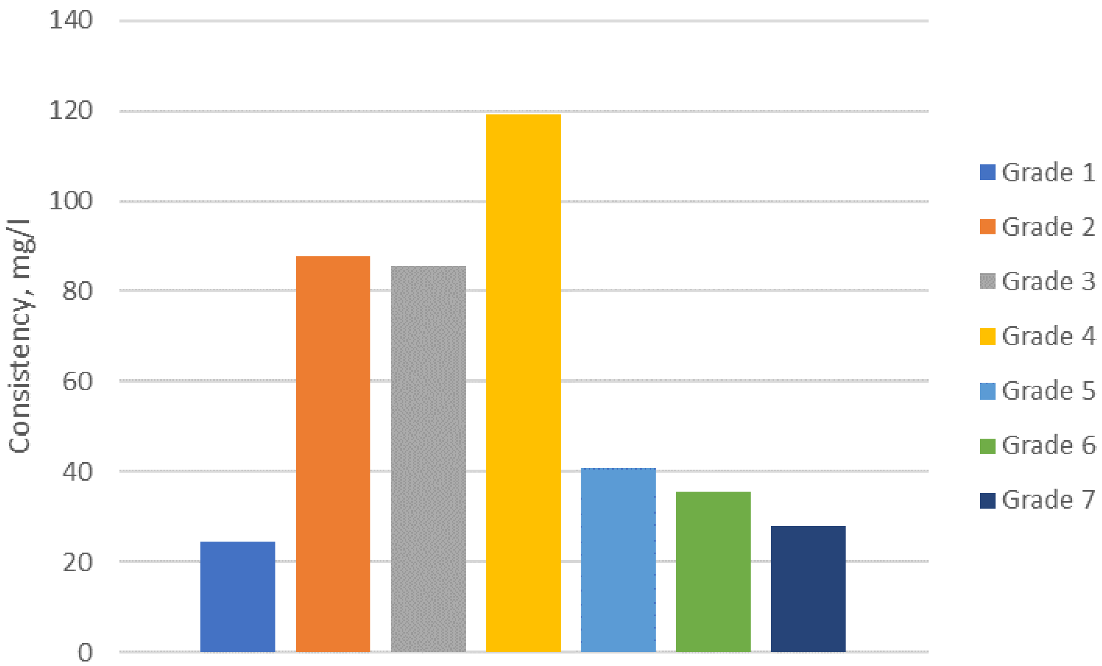

Figure 8. Middle layer wire water consistencies during production of various board grades.

As it can be seen from the Figure 8, during production of board grades 2, 3 and 4 the middle layer wire water consistencies were significantly higher than on the other grades. Because the grades 2 and 3 are quite commonly produced grades, but grade 4 is not a very common one, it was decided to perform the test run during the production of grade 2 or 3. The reason for doing the test run when the solids content in the process water is high, is that the filtrate water filter could clog more easily, and the results from the test run would be clearer than with low solids content.

10.1 Test run with the filtrate water filter

The test run studying the operation of the filtrate water filter was conducted during 9.3.2021–12.3.2021, because at that time the desired board grade was in production. The test run consisted of four smaller test runs in which three parameters were varied. These parameters were the opening of the restricting valve (%), washing time (s) and break time (min). The opening of the restricting valve controls the flow through the filtrate water filter. Washing time is the time used for washing the filter in every wash, and the break time is the time between the washes. The parameters have normally the following values: 16 % for valve opening, 45 seconds for washing time and 3.4 minutes for break time. Here it is studied can the valve be opened more without causing the clogging of the filter. Valve openings from 16 to 20 % were used in the study. The different parameter combinations that were tried in the test run are presented with their dates and test run numbers in Table VI. The value of valve opening was gradually increased based on the behaviour of filtrate water filter's pressure difference. Suitable washing times were selected based on the upper limit of one minute, and reduction of the break time from 3.4 to 2.0 minutes was decided to be enough. The test run results are discussed later in this work. A separate internal report from the test run was produced for the company.

Table VI. The combinations of parameters' values used in the test run.

Date of test run	Test run number	Valve opening, %	Washing time, s	Break time, min
Normal operation	-	16	45	3.4
9.3.2021	1	17	45	3.4
10.3.2021	2	17	60	3.4
10.3.2021	2	18	60	3.4
11.3.2021	3	19	60	3.4
12.3.2021	4	19	30	2.0
12.3.2021	4	19	45	2.0
12.3.2021	4	20	45	2.0

At the beginning of the test run 1, the valve opening was changed from 16 % to 17 %, and it was decided that the inlet- and outlet pressure, and their pressure difference of the filtrate water filter would be observed for at least two hours before the water samples from super clear filtrate and shower water tank water would be taken. This was done, because it was assumed that the possible changes in the pressures would not occur immediately. The filter worked almost normally around 2.5 hours until a high increase in the pressure difference (115 kPa) was detected, although the filter washed itself already more frequently due to the pressure difference which was reaching its limit for automatic washing (60 kPa). The water samples were taken right after the high increase was noticed and it turned out that the solids content was higher than in any other samples before or during the test run. It was 11 mg/L in super clear filtrate and 9 mg/L in the shower water tank water, and earlier that day it had been 5 to 8 mg/L and 3 to 5 mg/L respectively (measured solids contents are presented in Appendix I). It seemed that the pressure difference stayed higher than normally and did not decrease after the valve opening was set temporarily lower (to 15 %), so the opening was set even lower (to 14 %). After a while, the pressure difference decreased and later the valve opening was set back to its normal position. The increase in the pressure difference might be caused by temporary increase in the solids content, which might have also occurred with the valve being 16 % open. Presumably, the filter clogs when solids content raises high enough. Therefore, by lowering the flow through the filter, the filter does not clog as significantly, and the pressure difference stays lower.

In the test run 2, the washing time was increased from 45 seconds to 60 seconds, and the valve opening was set 17 % open. This time the pressure difference stayed lower, but four hours after starting the test run the solids content was low in both water samples, which can explain the lower pressure difference, although also the washing time was 15 seconds longer in this test run. Since the filter worked normally, the valve was set to 18 % open, and the washing time was kept at 60 seconds. Four hours after increasing the valve opening, the solids content was at the same level as previously, and the filter worked normally, which supports the finding that on lower solids contents the filter works normally, and with higher solids contents it starts clogging.

Before starting the test run 3, the solids content was determined and it was quite low in the super clear filtrate, so the test run was performed by increasing valve opening to 19 % and keeping the washing time at 60 seconds. Just before the valve was set to 19 % open, the pressure difference started increasing, and 1.5 hours later the solids content had increased to 4.4 mg/L in the super clear filtrate, and two hours from that the solids content was 7.6 mg/L. The samples for the latter solids content were taken exactly at the time when the pressure difference had increased briefly to 150 kPa. This clearly indicates that there is a correlation between the high solids content of super clear filtrate and high pressure difference of filtrate water filter. Also, the solids content of shower water tank water was high at the same time, which could be caused by the high solids content in the super clear filtrate, if the filter lets some of the solids pass through.

As the Table VI shows, in the test run 4 three combinations of the parameters were tried. The solids content was low before starting the test run, and therefore the valve opening was set again to 19 %. The solids content increased during the test run, and so did the pressure difference of the filtrate water filter. The washing time was increased from 30 to 45 seconds to see if it would decrease the pressure difference, especially after the washing phases. Valve opening was increased to 20 % since the pressure difference stayed a while at normal level. The observations made during the last test run strongly support the previous finding that higher solids content in super clear filtrate is the cause for higher pressure difference in the filtrate water filter. The results from all test runs are discussed in more detail later in this work.

10.2 Solids content measurements

Just before starting the test run, in total six water samples from the super clear filtrate and shower water tank water were taken for determination of solids content in the waters. One sample was taken from both waters at a time, and each pair of samples were taken one hour apart from each other. This was performed to see if there is some temporal fluctuation in the solids content of the waters. To get representative samples, they were taken from the first possible place in the pipeline leaving both the super clear filtrate tank and the shower water tank. The sampling point for the super clear filtrate is shown in Figure 9 and for the shower water tank water in Figure 10. The volume of the samples was approximately one litre, and they were taken manually.

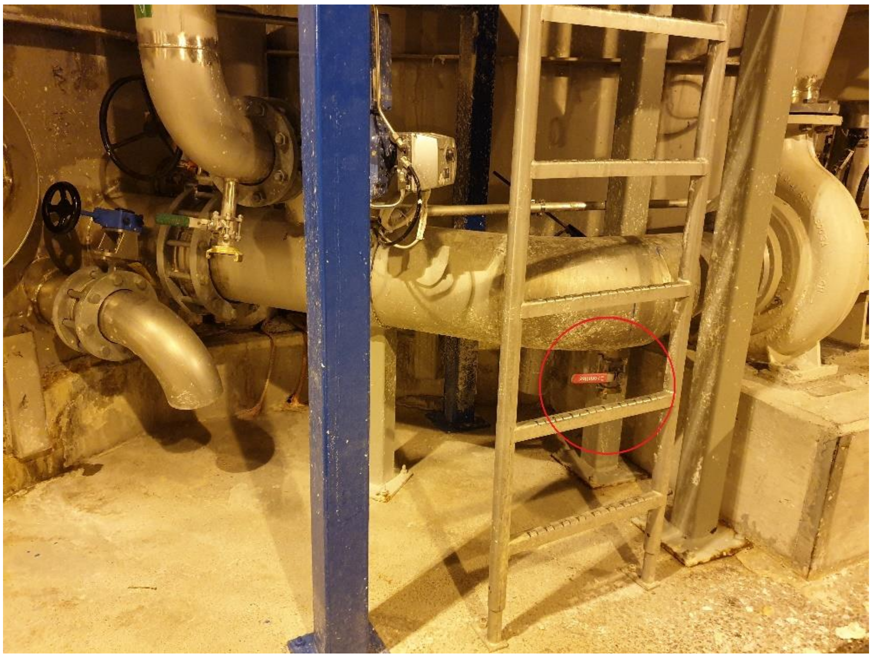

Figure 9. The sampling point for the super clear filtrate is located right at the outlet of filtrate water tank.

Figure 10. The sampling point for the shower water tank water is next to the tank.

The solids content was analysed by first weighing the sample and filtrating it through an already weighed Whatman grade 589/3 quantitative filter paper, which should not allow particles larger than 2 µm pass the filter. After the filtration, the filter paper was dried in temperature of 176-177 °C and weighed. By using the masses of the dry sample and the original wet sample the solids content was calculated using equation (1). Instead of measuring the volume of the liquid sample, it was weighed, and by assuming the water density to be 1000 kg/m^3 the result can be presented in mg/L unit. It was presumed that by weighing the liquid sample, the results would be more accurate, since more precise values could be obtained from weighing than measuring the volume of the sample, and in addition the water density would not affect the weighing.

$$SS = \frac{m(dry\ sample) \cdot 1000}{m(wet\ sample) \cdot 0{,}001} = \frac{m(filter\ paper\ and\ sample) - m(filter\ paper)}{m(sample\ and\ container) - m(container)} \cdot 1000000 \quad (1)$$

where SS solids content, mg/kg ≈ mg/L

m mass, g

Based on the deviation of solids contents of the first six samples, it was decided that during the test run two parallel samples will be taken from both the super clear filtrate and the shower water tank water, and their average values will be calculated to improve the accuracy of the measurements. The solids content in the first samples varied approximately from 5 to 8 mg/L in the super clear filtrate and from 3 to 5 mg/L in the shower water tank water.

During the test run period the solids content was determined from 62 samples. The average difference between the solids content of parallel samples was 1.2 mg/L in super clear filtrates and 1.3 mg/L in shower water tank water, which is quite accurate result considering the low content of the solids. Still, there were two samples that had significantly higher difference between parallel solids content (3.7 mg/L and 5.8 mg/L), but they were included in the study. The variation in the solids content values of the parallel samples can originate from the analysing of samples, the sampling itself, and rapid changes in the solids content of the waters. The parallel samples could not be taken exactly at the same time, and therefore also the rapid changes in solids content are a possible cause for the variation of the results. The measured solids contents are presented in Appendix I.

Sampling of the super clear filtrate was more difficult than sampling of shower water tank water, since the super clear filtrate was in higher pressure, the valve was larger, and the filtrate foamed quite vigorously. Super clear filtrate samples looked cloudier than the shower water tank water samples, but they were still quite clear. It was also noted that sometimes in the shower water tank water samples there were a few very small dark particles, which were not observed in the super clear filtrate samples. The size of those particles was estimated to be much smaller than 1 mm, and their source is still unknown. The particles may have passed through the treatment of fresh water and ended up to the warm water tank, from which part of the water has been transferred to the shower water tank.

10.3 Results and discussion from the test run

During the test run 9.3.–12.3.2021 vast amount of data was produced from the existing online meters. The data of inlet- and outlet pressure, and their pressure difference from the filtrate water filter gathered from the test run was taken from Wedge, and it was compared to the solids content measurements which were made manually in the laboratory. Also, other data was examined using the Wedge, to understand what the reason for fluctuation of the solids content in the super clear filtrate could be. Since the solids content fluctuated during the test run, it was somewhat difficult to determine whether changing some of the parameters had an effect to the operation of the filtrate water filter or if it was affected by the solids content coincidentally at the same time.

The inlet- and outlet pressures, together with the pressure difference of the filtrate water filter from the test run 1 are shown in Figure 11 (p. 55). As can be seen, the inlet pressure stays somewhat constant, which it normally does. Instead, the outlet pressure decreases and rises repeatedly. The decrease in the outlet pressure is due to the deposition of particles on the filter surface (clogging), which is reversed, when the filter is automatically washed, lifting the outlet pressure back to original level. Because the inlet pressure stays almost constant, the pressure difference fluctuates very similarly to the outlet pressure but inversely. The filtrate water filter also uses the pressure difference for determining if the filter needs to be washed before the timed washing. The pressure difference is of interest because it provides information about the clogging of the filter.

In the Figure 11 (p. 55) there is a rapid increase in the pressure difference, and at that moment the super clear filtrate's solids content was determined to be the highest of the whole test run (solids content measurements are presented in Appendix I). Also, near that time the filter washes itself more frequently, which can be seen from the fluctuation in the pressure difference curve getting denser. Before the test run the solids content was lower, and at that moment also the pressure difference was lower. Based on this information, it seems that the solids content of super clear filtrate correlates with the pressure difference of the filtrate water filter.

In Figure 12 (p. 55) the pressure difference of filtrate water filter, flowrate of dilute broke to the disc filter, inlet pressure of the first step of centrifugal cleaning, and the consistency of broke entering the first step of centrifugal cleaning are presented from the test run 3. The Figure 12 shows that the pressure difference was at low level at the beginning, as was the solids content of the super clear filtrate. Just before the valve was changed from 16 % to 19 % the pressure difference started to increase. The samples taken reveal that the solids content had increased after the valve opening was changed. When the pressure difference was temporarily at very high level (approximately 150 kPa) the solids content was determined to be 7.6 mg/L, which is quite high. Later, as the pressure difference suddenly dropped, water samples were taken. These samples revealed that the solids content had also decreased. Subsequently, the solids content had increased a little, and so had the pressure difference. Based on these observations, it seems that higher solids content in the super clear filtrate leads to clogging of the filtrate water filter.

In Figure 12 also the flowrate of dilute broke to the disc filter, the inlet pressure of first step of centrifugal cleaning, and the consistency of broke entering the centrifugal cleaning were compared to the pressure difference of the filtrate water filter. The reason why these are examined together is that the dilute broke enters the first step of centrifugal cleaning, from which the accept is led to the feed of the disc filter. From the disc filter the super clear filtrate is led to the filtrate water filter, and therefore they are connected to each other as it is shown in the Figure 5. The cause for fluctuation in the pressure difference is likely to be found from the earlier stages just before the filtrate water filter.

First it seems that in Figure 12 the flowrate could be connected to the increase in pressure difference, but when taking a closer look, the flowrate stays constant as the rapid increases in the pressure difference occur. Instead, the broke consistency either increases or decreases at those points, so the changes in broke consistency seem to have some connection to the pressure difference. It might be that when the broke consistency changes, the disc filter lets more of solid particles pass through, causing the solids content of the super clear filtrate to raise, which then leads to clogging of the filtrate water filter. It is still possible that also the flowrate affects the pressure difference, at least if it changes substantially. Figure 12 shows also that the inlet pressure of the first step of centrifugal cleaning correlates very strongly with the flowrate to the disc filter, which seems logical.

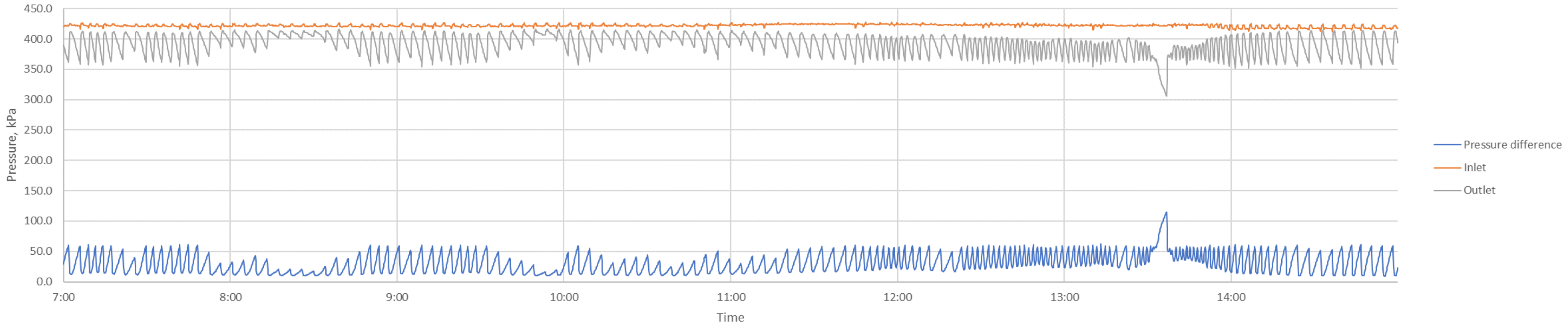

Figure 11. The inlet- and outlet pressure, and their pressure difference of the filtrate water filter during the test run 1.

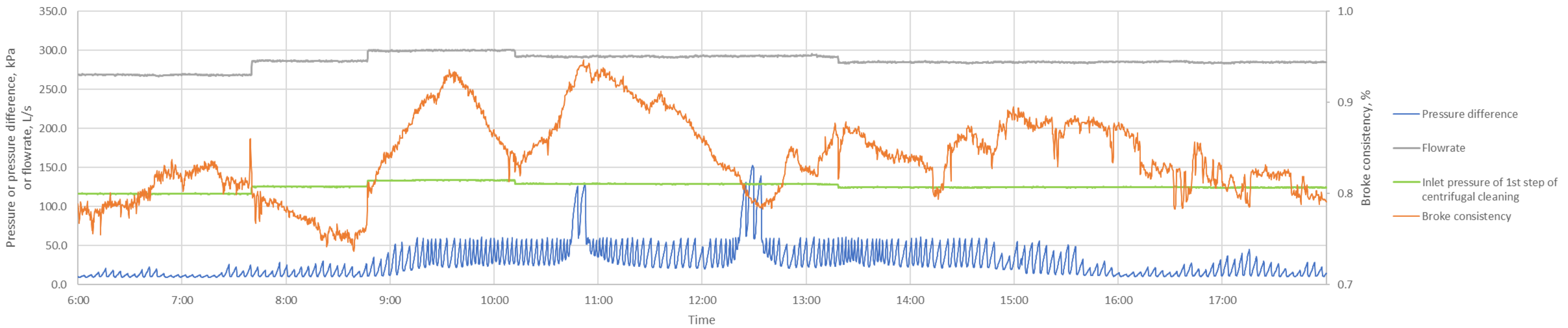

Figure 12. The pressure difference of the filtrate water filter, flowrate of dilute broke to the disc filter, inlet pressure of first step of centrifugal cleaning, and broke consistency before the first step of centrifugal cleaning during the test run 3. The right axis is cut to make the broke consistency curve clearer.

In Figure 13, the pressure difference, flowrate of dilute broke to the disc filter and the broke consistency before the centrifugal cleaning is shown. The connection between the broke consistency and the pressure difference is seen also in this figure. As shown in Figure 13, the flowrate of dilute broke to the disc filter stays almost constant and so does the broke consistency at first, but it starts increasing after a while. At that time, changes are also seen in the pressure difference curve. When the broke consistency suddenly drops and starts slowly decreasing, also the pressure difference drops and starts decreasing. Sometimes the changes in the broke consistency do not seem to have effect to the pressure difference, but it might be due to low enough solids content, or maybe there is some other cause for the increases in the pressure difference.

The effect of changing valve opening, washing time or break time was difficult to determine, since it seemed that the solids content in the super clear filtrate had stronger effects to the pressure difference. The pressure difference and the valve opening are plotted together in Figure 14 to see if changing the valve opening has an instant effect to the pressure difference. This specific time for examining the effect to the pressure difference was selected, because the valve opening was changed from 19 % to 16 %, and although the pressure starts increasing steadily, there is simultaneous drop in pressure difference as the valve position is changed. This provides information about the pressure difference caused by the change in valve position, and it is marked in the figure with "+" marks. It shows that closing the valve opening by 3 %, the pressure difference is dropped by 9.6 kPa in this case. For comparison, also the pressure differences after the filter's automatic washing phases are observed and these are marked with "x". The pressure difference decreased in this case by 6 kPa. Similar instant change in pressure difference was detected also at other times when the valve position was changed. By closing the valve more, the outlet pressure increases, which also causes the decrease in the pressure difference.

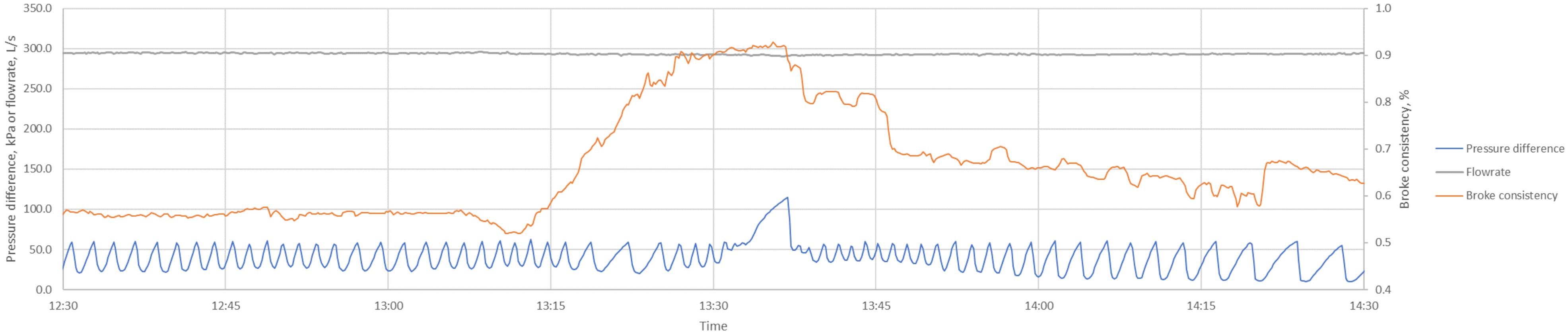

Figure 13. The flowrate of dilute broke to the disc filter, broke consistency before the first step of centrifugal cleaning, and pressure difference of the filtrate water filter during the test run 1. The right axis is cut to make the broke consistency curve clearer.

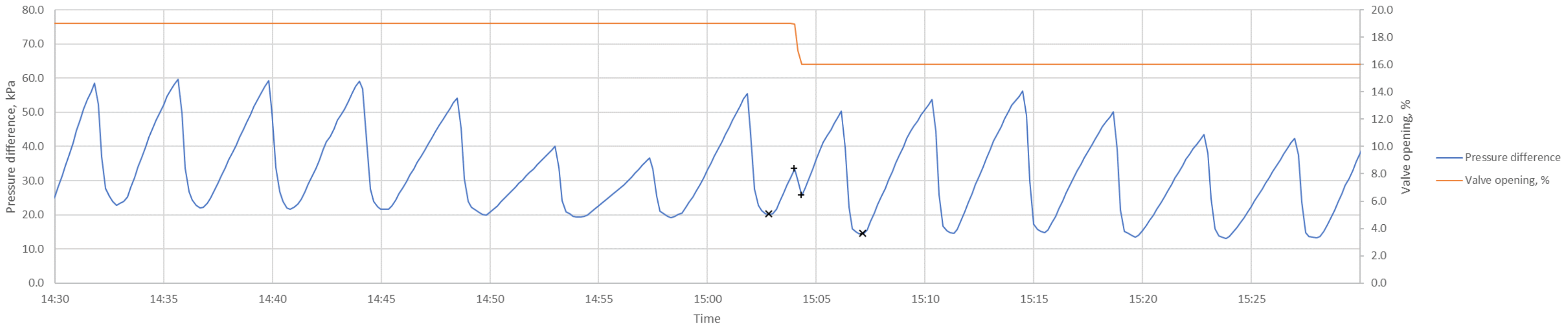

Figure 14. Effects of changing valve opening from 19 % to 16 % in the test run 3. The "+" marks indicate the moment when the valve position was changed. The "x" marks are for comparison of the pressure differences after the automatic washing phase. Washing time was also changed from 60 seconds to 45 seconds, but it did not cause the pressure drop seen between the "+" marks.

When changing the break time between washes from 3.4 minutes to two minutes and washing time from 45 to 30 seconds during the test run 4, the pressure difference was dropped at first, but it increased after 20 minutes, although also the solids content had increased during the beginning of the test run. Before the test run the solids content in super clear filtrate was low, but two hours later the solids content had increased significantly. This would explain the increase in the pressure difference. Therefore, shortening the washing time and the break time between washes as described can help keeping the pressure difference low. Although, 30 seconds washing time might not reduce the pressure difference as low as washing time of 45 seconds would, and during a higher pressure difference the flow through the filter might be lower.

Shortening the break time between washes increases the share of time used for washing the filter. This means that although the filtration continues simultaneously during the washing, reject is also formed. In other words, increasing the share of time used for washing increases the amount of produced waste. The share of washing time from the total operation time of the filtrate water filter is compared in Table VII using the values from the test run. As can be seen, by reducing the break time from 3.4 to 2.0 minutes while keeping the washing time at 45 seconds, the share of washing time increases 9.1 %. For the shortening of the break time to be beneficial, the flow of super clear filtrate should increase from the reduced clogging as the share of washing time is increased. The amount by which the clogging reduces the flow through the filter is unknown since there is currently no flow meter for the super clear filtrate flow. The reduced break time did not seem to improve the pressure difference noticeably when the solids content was at higher level.

Table VII. The share of filtrate water filter's washing time of the filter's total operational time.

Washing time, s	Break time, min	Share of washing time, %
45	3.4	18.1
60	3.4	22.7
30	2.0	20.0
45	2.0	27.2

To see if changing the washing time would affect the pressure difference, all other parameters were kept the same when the washing time was increased from 30 to 45 seconds. Since the pressure difference varies greatly over time, the effects of changing the washing time are difficult to see with long time period, and therefore a short period (40 minutes) is examined in Figure 15, in which the pressure difference is plotted with the washing time. In Figure 16 longer time interval is used and additionally valve opening is shown from the same test run.

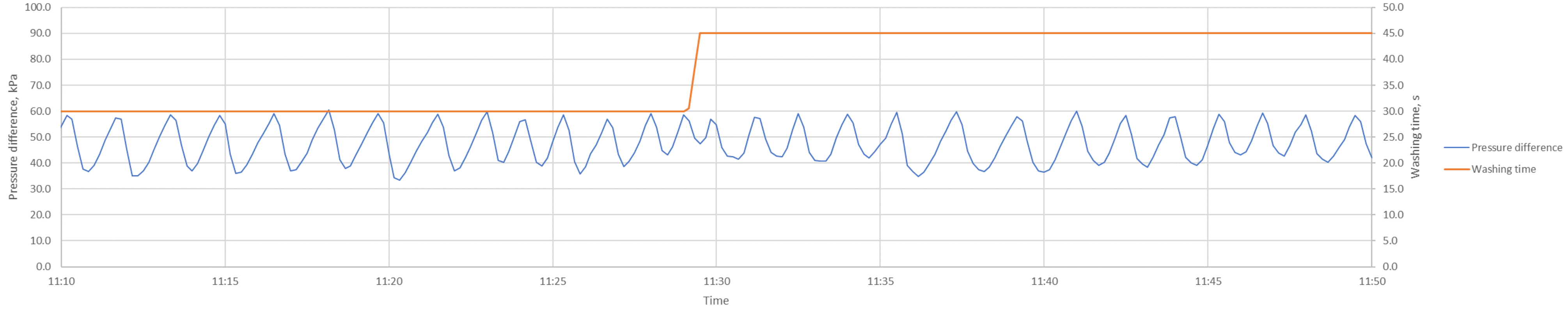

Figure 15. The effect of changing washing time from 30 seconds to 45 seconds in the test run 4. Valve opening was 19 % and break time between washes was 2.0 minutes.

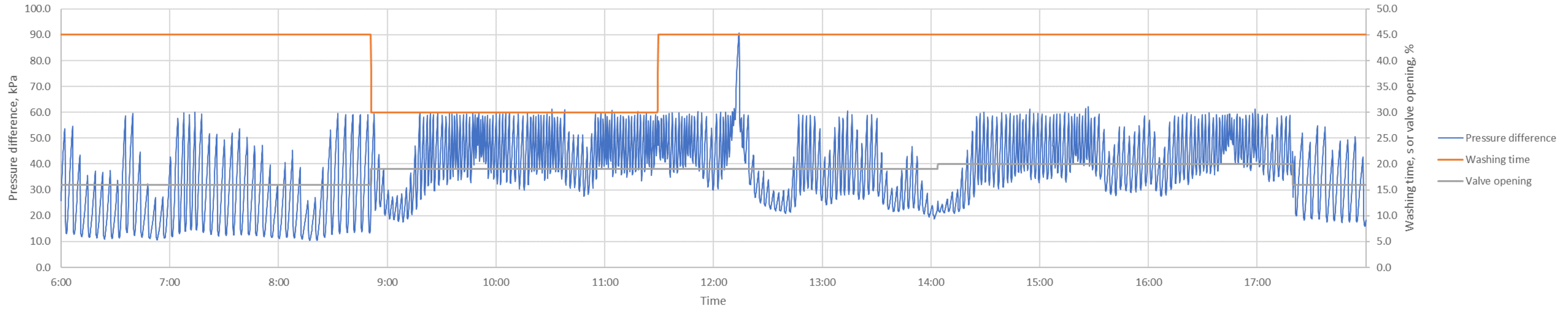

Figure 16. The pressure difference and washing time of the filtrate water filter, and the valve opening in the test run 4. Break time between washes was changed from 3.4 to 2.0 minutes when the valve opening was changed from 16 % to 19 %, and it was returned to 3.4 minutes when the valve opening was changed from 20 % to 16 %.

Presumably by increasing washing time the pressure difference should get lower, but as showed in Figure 15, changing the washing time from 30 to 45 seconds did not seem to affect the pressure difference significantly. It might be that when the solids content is high enough, increasing the washing time by 15 seconds is not enough to decrease the pressure difference.

Figure 16 shows that the pressure difference can vary significantly even during the times the valve position, washing time and the break time between washes remains unchanged. By comparing the pressure difference data to the solids content of the super clear filtrate, it is seen that when the solids content was high, the pressure difference was also at high level. As the pressure difference dropped, the solids content was 0 mg/L. This is important observation, and it correlates with the previous findings of this work. The filter works normally with the higher valve opening of 19 % when the solids content is zero, meaning that the higher pressure differences are caused by real clogging, not only because of the higher valve opening and therefore the drop in the outlet pressure. In addition, the lowest pressure difference was around 20 kPa on low solids content when the valve was 19 % open, but earlier when the solids content was low the pressure difference was 12 kPa with valve being 16 % open. Their difference, 8 kPa is close to the previous observation, where closing the valve by 3 % reduced the pressure difference by 9.6 kPa. The values presented here might not be in decimal accuracy since there is some fluctuation in the pressures of filtrate water filter and the solids content.

In Figure 17 the pressure difference of filtrate water filter, the valve opening, and the washing time is shown from the test run 2. As the figure shows, only the lowest values of pressure difference are increased a little when the valve opening is increased, but the pressure difference stays otherwise unaffected. Since the solids content was low during the test run (1.2-1.7 mg/L), it explains why the pressure difference stayed at normal level. Changing the washing time from 45 to 60 seconds or vice versa did not seem to affect the pressure difference significantly. In Figure 18 flowrate to the disc filter and broke consistency before the first step of centrifugal cleaning from the same test run is shown.

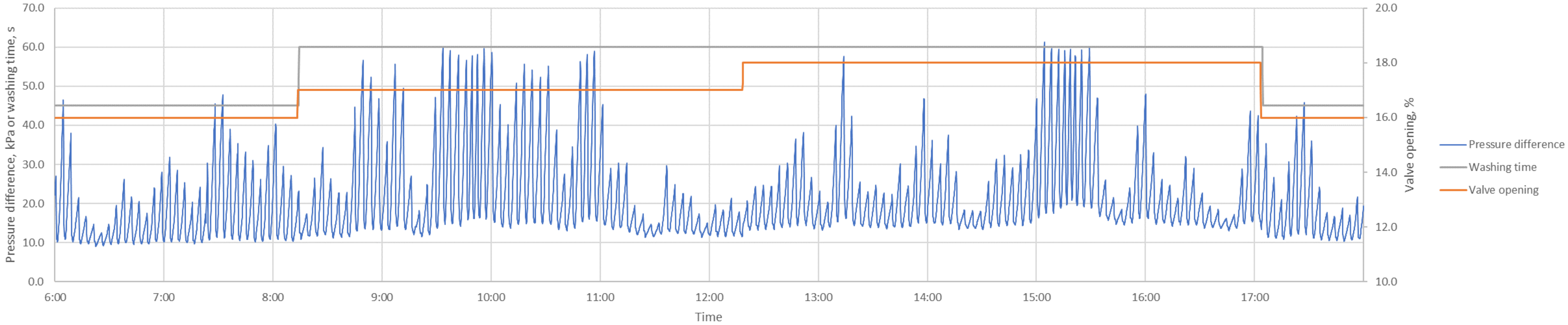

Figure 17. Pressure difference of the filtrate water filter, the valve opening, and the washing time during the test run 2. Break time between washes was 3.4 minutes.

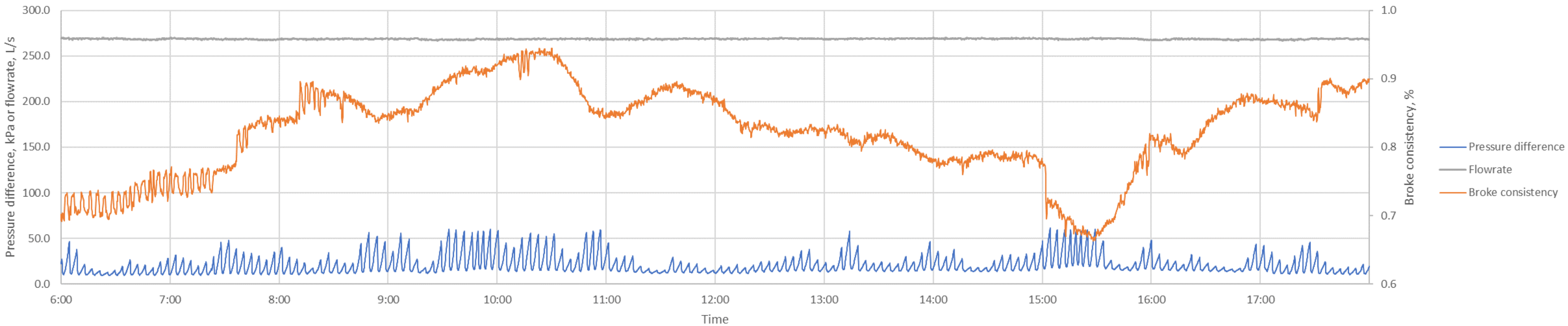

Figure 18. Pressure difference of the filtrate water filter, flowrate to the disc filter, and the consistency of broke entering the first step of centrifugal cleaning during the test run 2. Break time between washes was 3.4 minutes.

The pressure difference shown in Figure 18 stays at normal level, but it fluctuates. The flowrate stays somewhat constant, which shows that it does not cause the fluctuation of the pressure difference in this case. Instead, there is some similarity in the broke consistency data when compared to the pressure difference, although it is not always consistent. It seems that often when there is some type of change in the broke consistency, especially rapid one, the pressure difference either increases or decreases (see Figure 12, Figure 13, and Figure 18).

Since the solids content were determined from both the super clear filtrate and the shower water tank water, their values were compared together to see if there is any correlation between them. The results from the comparison are shown in Figure 19. Parallel samples were taken from both waters for each data point, and the samples of both waters were taken only a few minutes apart, so they can be considered to represent the same time.

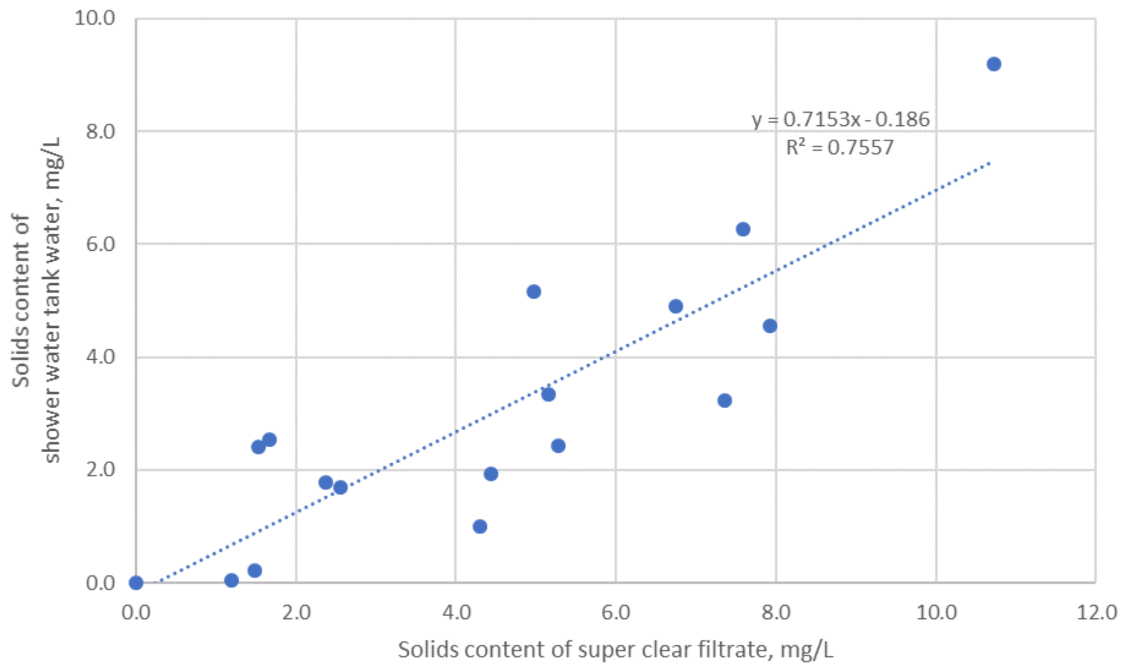

Figure 19. The relation between solids content of the super clear filtrate and the shower water tank water. Linear regression line with its equation and coefficient of determination is also shown.

As the Figure 19 shows, the solids content in the shower water tank water is mainly smaller than in the super clear filtrate, as it should be. If the solids content of shower water tank water is higher than that of the super clear filtrate, it is probably due to inaccuracy of the measurement, since the measured solids contents are quite low, or due to the fact that the samples are not taken exactly at the same time. Figure 19 reveals that there is clearly some correlation between the two solids contents, although there is also some variation in the data. The value of the coefficient of determination (R^2) is relatively high, which indicates that there is a correlation between the two solids contents. The solids content in the shower water tank water seems to increase as the solids content of the super clear filtrate increases. This indicates that in the super clear filtrate there are particles smaller than 150 µm, which go through the filtrate water filter and end up in the shower water tank. To see if some narrow fibres pass through the filter, further analysis of the waters was carried out.

In Table I of the literature part some quality requirements for the solids content of shower water were introduced. If the table is compared to the Figure 19, it is seen that during the test run the solids content of the super clear filtrate has been so low, that based on the solids content it could be used in the same shower water applications as the fresh water.

The solids content of shower water tank water was also compared to the valve opening which was used at the time when the samples were taken. The filtrate water filter's washing time and break time between washes were not the same for all samples, but presumably they do not affect the solids content significantly. The solids content of shower water tank water on different valve openings is presented in Figure 20.

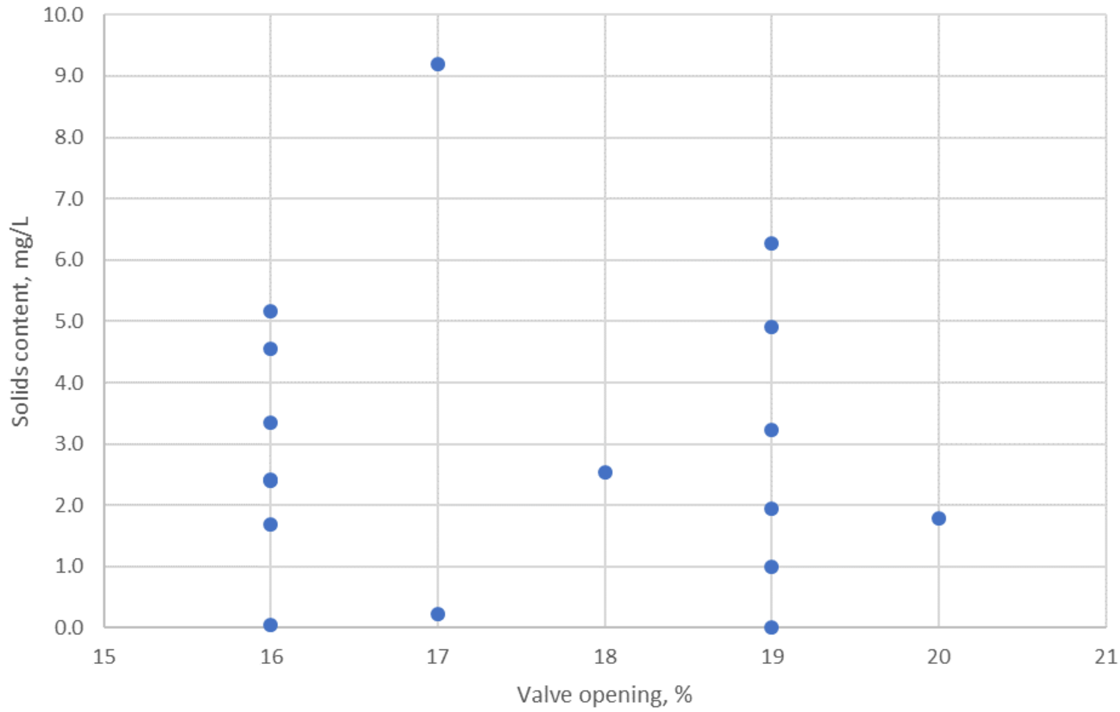

Figure 20. Solids content of shower water tank water on different valve openings.

Even though there are not so many data points in the Figure 20, it still shows that the solids content varies significantly on different valve openings. Therefore, increasing the valve opening by a few percent does not seem to noticeably affect the solids content of the shower water tank water. It is possible that increasing the valve opening higher than in the test run could increase the solids content in the shower water, however the solids content should not get higher than that of the super clear filtrate.

Since the solids content of shower water seemed to be related to the solids content of the super clear filtrate, it was examined, do the fibres from the super clear filtrate end up in the shower water tank. Valmet Fiber Image Analyzer (Valmet FS5) was selected to be used for analysing the water samples. Valmet FS5 is an analyser designed especially for use at pulp and paper mills (Valmet, 2021b). It can perform several automated measurements such as length and width of the fibres from liquid samples, and it also adjusts the consistency of the samples automatically. In this case, one sample was taken from both the super clear filtrate and the shower water tank water, and they were analysed by the laboratory personnel. The volume of a sample was one litre, and parallel determinations were made from both samples.

In addition, the solids content was determined from both waters at the same time when the samples were taken.

The solids contents of the analysed super clear filtrate and shower water tank water were quite low but despite that, results were obtained from the Valmet FS5 analyser. It was discovered that fibres indeed existed in the shower water tank water. The analyser recognizes the fibres from other particles and calculates the average lengths and widths, and the length distribution for fibres of different length. Fibres having a width greater than or equal to 5 µm were included in the analysis results. The average fibre length and width with the number of measured fibres for both water samples are presented in Table VIII.

Table VIII. Average length, average width, and number of fibres determined from the super clear filtrate and the shower water tank water using Valmet FS5.

Sample	Average fibre length, mm	Average fibre width, µm	Fibre count
Shower water tank water	0.39	15.86	104919
Super clear filtrate	0.458	17.61	120712

As the Table VIII shows, the average length of fibres in the shower water tank water is 390 µm and it is clearly higher than the filtration grade of the filtrate water filter, which is 150 µm. This can be explained by the average width of the fibres, which is only 15.86 µm in the shower water tank water. These fibres are so narrow that when they hit the filter in a suitable position, they can pass through the gaps of the filter. The table also shows that the number of measured fibres, and the average length and width of the fibres is smaller in shower water tank water, which indicates that the filter removes larger particles. The number of analysed fibres seems high in both water samples so the results of the analysis can be considered quite reliable.

The fibre length distribution provides more specific information about the fibres, and it is presented in Figure 21 for both the super clear filtrate and the shower water tank water. The figure shows the share of fibres belonging to a certain length range, or fraction.

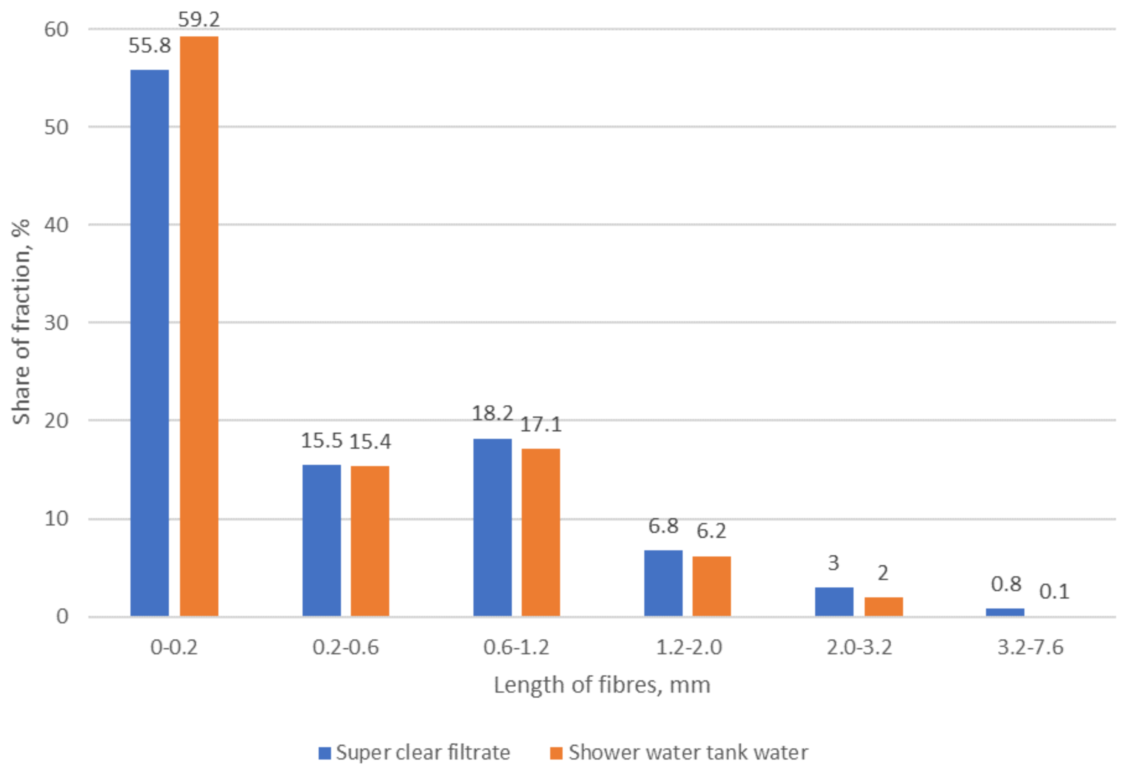

Figure 21. The length distribution of fibres in the super clear filtrate and the shower water tank water. The fibre width is greater than or equal to 5 µm.

As the Figure 21 shows, the fibre length distributions are quite similar in both waters, which supports the finding that the solids content of the super clear filtrate correlates with that of the shower water tank water (see Figure 19). It strongly seems that part of the fibres passes through the filter and ends up in the shower water tank, because the fibre width is smaller than the filtration grade of the used filtrate water filter.

In Figure 21 most of the fibres in both waters belong to the first fraction having a fibre length between 0 and 0.2 mm. In this fraction, the shower water tank water has higher share than the super clear filtrate, which is reasonable, since the filtrate water filter removes the larger particles, thereby increasing the share of smaller particles in the shower water tank water. Therefore, the super clear filtrate has higher share in other fibre fractions which contain longer fibres.

The share of fraction containing fibre lengths 2.0-3.2 mm is 2 % in Figure 21, and even in the fibre length fraction of 3.2-7.6 mm there is still 0.1 % share of fibres in the shower water tank water. It is interesting that even some long fibres seem to pass through the filter. This might be due to the selected filter candles in the filtrate water filter, which have longitudinal gaps that seem to allow long but very narrow fibres to pass through the filter element in suitable position. If the filter element was wire mesh type, it might prevent more of the fibres from passing through the filter but there is also the possibility that it would clog more easily as the amount of rejected fibres would increase. The fibres might also get stuck more easily in the mesh type filter element.

As the solids content measurements were made, it was noticed that occasionally there were some larger fibre bundles in the super clear filtrate samples. These fibre bundles cannot pass through the filtrate water filter since they are several millimetres in size. This finding might explain the clogging of the filter. If more of these fibre bundles appear at the same time, they are likely to gather on the surface of the filter during the filtration and decrease the flow through it, hence increasing the pressure difference of the filter. Examples of these fibre bundles are shown in Figure 22.

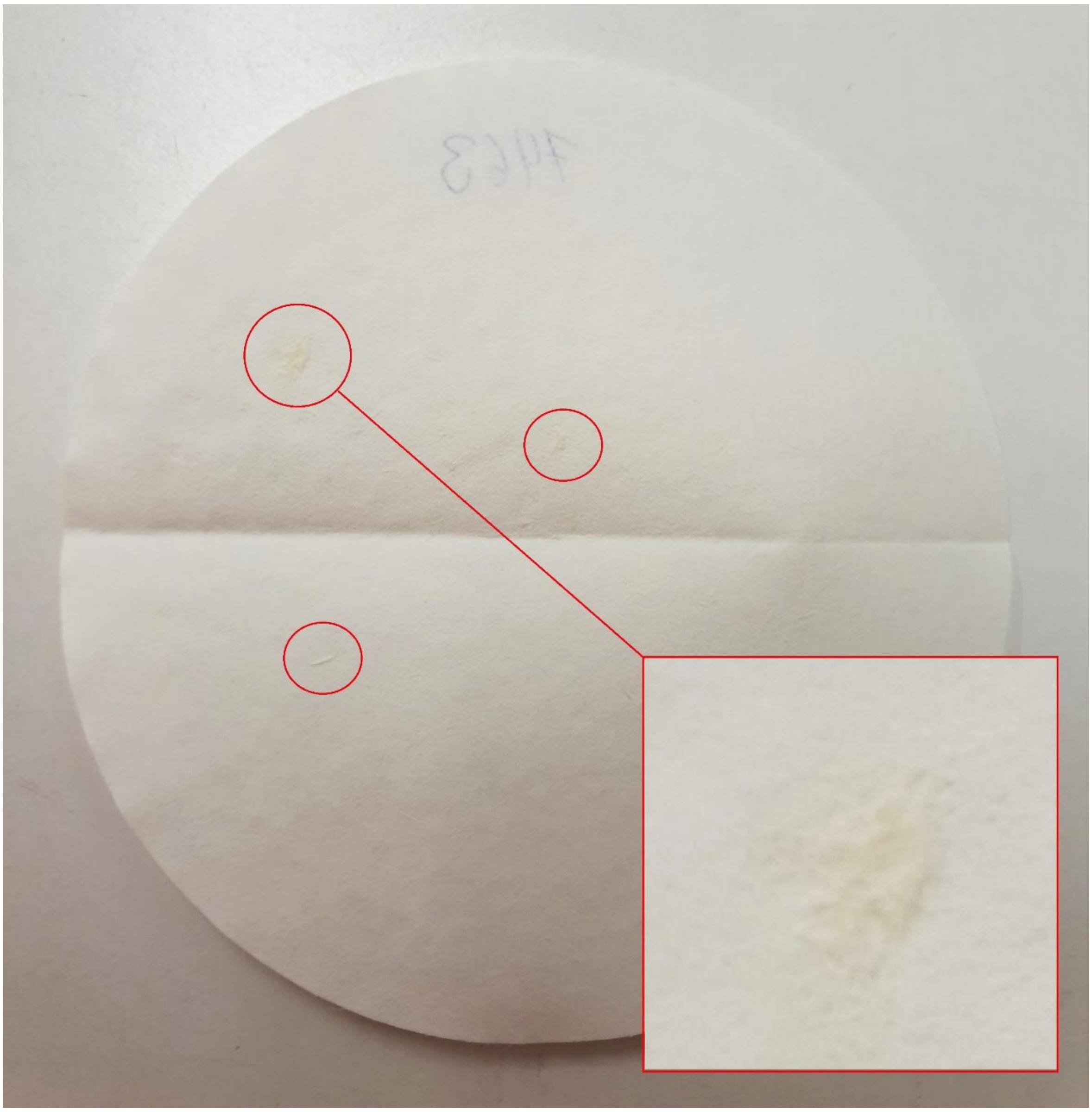

Figure 22. Fibre bundles found from the super clear filtrate after sample filtration during the solids content measurement. The size of the largest fibre bundle was approximately 3-4 mm.

The only way the fibre bundles can end up in the super clear filtrate is that the bundles pass through the disc filter for some reason. According to the company's ERP system, the current filter cloth material of the disc filter is metal and the pore size of the fabric is 770 µm. Therefore, the larger fibre bundles should not pass through the disc filter's fabric. Perhaps there is a damage in the fabric or possibly a small leakage in some of the connection points of the fabric.

Previously in this work it was noticed that the consistency changes in dilute broke fed to the disc filter seem to be linked to the pressure difference of the filtrate water filter. Maybe increases in the consistency of dilute broke entering the disc filter causes the disc filter to temporarily clog, and the fibres leak more easily, which then occurs as an increase in the pressure difference at the filtrate water filter as the fibres are gathered on the surface of the filter.

10.4 Conclusions from the test run

The test run was carried out to see if the amount of super clear filtrate produced by the disc filter could be increased in the shower water tank without clogging the filtrate water filter and without reducing the quality of shower water. The opening of the restricting valve, the washing time, and the time between washes of the filtrate water filter were varied to test if the valve could be opened more without clogging the filter. To understand what the reason behind the clogging might be, the Wedge data from inlet- and outlet pressure and their pressure difference, dilute broke consistency, and flowrate to disc filter were studied. Some other data from Wedge were also studied, but they did not seem to correlate to the high pressure differences in the filtrate water filter. In addition, solids contents and dimensions of fibres were determined from both the super clear filtrate and the shower water tank water, to see if the quality of the shower water was affected by the use of the super clear filtrate.

It was difficult to see the effects to the pressure difference level of the filtrate water filter when the washing time and the time between washes were changed, since the fluctuating solids content seemed to have stronger effects. Increasing the washing time did not seem to affect the pressure difference of filtrate water filter significantly when the solids content was high. Shortening the break time between washes might reduce the pressure difference level at low solids contents, but at high solids contents it did not seem to help remarkably. The current settings of the washing time and the break time are at somewhat optimal level, since changing them did not seem to improve the pressure difference. In addition, increasing the washing time or decreasing the break time would increase the amount of produced reject. Increasing the valve opening by 1 % with the current washing time and break time, the filtrate water filter seemed to work properly for part of the time, but it is likely that the automatic washing phases would get more frequent with the higher opening in the long term. If the pressure limit which starts the automatic washing could be increased a little, the time used for washing and hence producing the reject might be decreased, but there is a risk that the filter clogs more permanently and will not get clean.

During the test run it was observed that changing the restricting valve opening by 1 % seems to instantly change the pressure difference of the filtrate water filter by 1-3 kPa when the valve was opened more than 16 %, which is the normal setting. It is difficult to provide exact values on how much the pressure difference changes by changing the valve opening, because there is some fluctuation in the pressure data and the pressure difference is also continuously changing. Higher opening of the valve seems to decrease the outlet pressure and thereby increase the pressure difference, which is seen as an instant increase in the pressure difference as the valve is opened more. Other pressure difference changes that occurred later after changing the valve position were probably mainly caused by the variation in the solids content of the super clear filtrate. The valve opening seems to have an effect to the lowest value that the pressure difference can be reduced after the washing phase of the filtrate water filter.

In the test run it was noticed, that even during production of the same grade (Grade 2), the solids content can vary significantly in the super clear filtrate. In this test run the solids content varied between 0–11 mg/L. Although the exact reason for the variation is unknown, a probable explanation is that it originates from the operation of the disc filter.

The flowrate to the disc filter and the inlet pressure of the first centrifugal cleaning step are strongly related. Although, there was no clear connection between the pressure difference of filtrate water filter and flowrate to the disc filter, or between pressure difference of filtrate water filter and the inlet pressure of the first step of centrifugal cleaning, it is possible that changes in the centrifugal cleaning cause some variation in the solids that end up to the disc filter. This can then affect the operation of the disc filter and eventually the solids content of the super clear filtrate.

A clearer connection was seen between the broke consistency changes and the pressure difference of the filtrate water filter. Broke consistency changes affect the pressure difference by influencing the operation of the disc filter, although the connection is not always seen. It can be that the connection is only seen when the broke consistency or the solids content in the super clear filtrate is high enough. Sometimes it seemed that the pressure difference increased a little for no reason. It is likely that the disc filter lets occasionally more of the particles through due to damaged fabric, leakage, or some other cause, which then increases solids content in the super clear filtrate and causes the pressure difference of the filtrate water filter to increase. This is also supported by the finding, that there were some larger fibre bundles in the super clear filtrate, which were several millimetres in size and should not get through the disc filter. One possible explanation is that when the broke consistency increases too much, the disc filter kind of clogs temporarily and leaks from somewhere more easily, increasing the solids content of the super clear filtrate.

The clogging of the filtrate water filter seems to be mainly caused by the occasional high solids content in the super clear filtrate. At least solids contents over 7 mg/L seemed to cause significant pressure differences in the filtrate water filter. The fibre bundles found in the super clear filtrate may also cause the clogging of the filtrate water filter if they occur in larger quantities. At low solids content of a few milligrams per litre, it would be possible to open the restricting valve more, for example to 20 % or even higher, and thereby increase the flow of super clear filtrate to the shower water tank.

The solids content in the super clear filtrate seems to affect the solids content in the shower water tank water, but increasing the valve opening by a few percent and hence the flow through the filtrate water filter, did not seem to noticeably increase the solids content in the shower water. Apparently, some fibres do currently end up in the shower water tank. Since the solids content in the shower water tank should not in any case get higher than that of the super clear filtrate, and shower water tank’s solids content has already been occasionally almost as high as in the super clear filtrate, it is likely that increasing the use of super clear filtrate would not cause shower plugging problems at BM4. Finer filtration grade or different type of filter element of the filtrate water filter may prevent the fibres from ending up in the shower water tank, but it may also increase the clogging of the filter.

To use more of the super clear filtrate in the shower water tank, the valve may be adjusted or programmed to adjust its opening based on solids content or pressure difference data. If the dilute broke consistency changes do cause the higher solids contents of the super clear filtrate, then the solution is to smooth the consistency changes in some way, for example by installing to the pipeline a tank in which the consistency can be accurately adjusted. To utilize significantly greater amount of super clear filtrate in the shower water tank than currently, the surface area for filtration needs to be increased. This can be implemented by acquiring a larger filtrate water filter, or several filters that would be used in parallel.

10.5 Further research

As it was noticed in the test run, there were some fibre bundles in the super clear filtrate. It would require further studying to find out where these exactly come from. There might be damage in the fabric of the disc filter, or some other leakage. If there is a leakage in the disc filter, repairing it may improve the operation of the filtrate water filter in case these fibre bundles are causing the observed high pressure differences. Changing the filter cloth of the disc filter to one having smaller pore size would probably reduce the amount of solids that end up in the super clear filtrate, but this possibility and its effects to the operation of the disc filter would need to be examined first.

Adjusting the disc filter’s ratio of produced clear and super clear filtrates may also help to reduce the solids content of the super clear filtrate. If the super clear filtrate is produced too early so that the cake layer is not dense enough, more solids can get into the super clear filtrate. This would also require further examination.

A connection between the dilute broke consistency before the first step of centrifugal cleaning and the high pressure difference of the filtrate water filter was seen. Further research would be needed to discover if adjusting the consistency fed to the disc filter would affect the solids content of the super clear filtrate in a positive way. In addition, smoothing the changes in the consistency might help reducing the amount of solids that pass through the disc filter.

One possibility to increase the use of super clear filtrate in the shower water tank would be to use higher valve openings on such board grades in which high solids content in the super clear filtrate does not occur, but this would require further examination and monitoring the pressure difference of the filtrate water filter. Another possibility would be to program the valve to adjust its opening based on the pressure difference data, but this might be difficult to implement in practise. Third option is to add an online meter for measuring the solids content of the super clear filtrate and to program the valve to adjust its opening based on the solids content data, and possibly based on the pressure difference data.

The possibility to program the restricting valve to open based on solids content of the super clear filtrate and pressure difference of the filtrate water filter needs some research. This would also require installation of online meter for measuring the solids content from the super clear filtrate. Additionally, a flow meter for measuring the super clear filtrate flow through the filtrate water filter would provide information of the actual flow rate. It would reveal if the flow decreases, and by which amount, at the times the pressure difference of the filtrate water filter increases. Also, the effects of changing the filter elements in the filtrate water filter to different fineness or to different type could be examined.

11 SUMMARY

This work was divided into literature part and experimental part. In the literature part the existing literature related to board manufacturing and supporting the work was gone through. This included the board process and the chemicals involved, the water system of a board machine and the used water fractions, impurities in the process waters and treatment of the waters, amongst other topics. In the experimental part the total consumption of five different water fractions were studied at board machine 4, and four of the fractions were selected for mapping of the water streams. In the mapping the applications using the selected water fractions were listed in a table by going through piping and instrumentation diagrams, process diagrams from DNA automation system, and by following the pipelines at the site. The purposes for the water uses were also listed for each application, and if an online flow meter for the application existed, an average consumption from one year period was included in the table. In addition, the possibility to reduce the water consumption of the board machine 4 was studied, and the filtrate water filter was selected as the subject of study. A test run, in which the operation of the filter was studied, was conducted. The aim was to examine if the flow through the filter could be increased and if it affects the solids content of the shower water.

In the mapping of the water streams it was noticed that the most frequent purpose for water use at board machine 4 was cooling of equipment. Since currently the cooling- and sealing waters are led mainly to sewer, it should be considered would it be feasible to lead some of these waters into the process instead. There are also a few liquid ring pumps which consume water. These can be replaced by turbo blowers to reduce the water consumption. In addition, the number of flow meters at board machine 4 could be increased for more accurate tracking of water consumption.

In the test run it was discovered that the current settings for the washing time, the break time between washes, and the opening of the valve restricting the flow through the filtrate water filter are at somewhat optimal level. Currently some fibres seem to end up in the shower water tank, although their concentration in the shower water tank is low, and they are not likely to cause plugging of shower nozzles. The occasional high pressure difference of the filtrate water filter seems to be caused by high solids content and possibly by some fibre bundles present in the super clear filtrate. The occurrence of the fibre bundles in the filtrate may be explained by a leakage at the disc filter and repairing it might improve the operation of the filtrate water filter. In order to significantly increase the use of super clear filtrate in the shower water tank, the surface area for the filtrate water filtration needs to be increased.

REFERENCES

Alén, R. & Selin, J., 2007. Deposit formation and control. In: R. Alén, ed. *Book 4: Papermaking chemistry.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 163-180.

Anon., 1991. *Papermachines general.* Karhula: Metlas.

BOLL & KIRCH Filterbau GmbH, 2021. *BOLLFILTER Automatic Type 6.18 / 6. 19.* [Online]
Available at: https://www.bollfilter.com/fileadmin/downloads/prospekte/automatic-filter-type-6.18-en-BOLLFILTER.pdf
[Accessed 7 4 2021].

Dahl, O., 2008a. Introduction. In: O. Dahl, ed. *Book 19: Environmental Management and Control.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 9-18.

Dahl, O., 2008b. Process modifications to reduce effluent loads. In: O. Dahl, ed. *Book 19: Environmental Management and Control.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 69-84.

Eiroma, E. & Huuskonen, J., 1983. Paperin ja kartongin pigmenttipäällystys. In: A. Arjas, ed. *Paperin valmistus, osa 1.* 2nd ed. Helsinki: Suomen Paperi-insinöörien yhdistys, pp. 323-343.

Holik, H., Tschudin, P. F. & Rentrop, G.-H., 2006. Introduction. In: H. Holik, ed. *Handbook of Paper and Board.* Weinheim: WILEY-VCH, pp. 1-19.

Honkamaa, J., 2008. Vacuum pumps. In: H. Paulapuro, ed. *Book 8, Papermaking part 1, Stock Preparation and Wet End.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 493-510.

Hynninen, P., 2008a. Raw water treatment. In: O. Dahl, ed. *Environmental Management and Control.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 55-68.

Hynninen, P., 2008b. Effluent treatment. In: O. Dahl, ed. *Environmental Management and Control.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 85-116.

Häggblom-Ahnger, U. & Komulainen, P., 2006. *Kemiallinen metsäteollisuus II: Paperin ja kartongin valmistus.* 5th ed. Helsinki: Opetushallitus.

Kiviranta, A., 2000. Paperboard grades. In: H. Paulapuro, ed. *Paper and Board Grades.* Helsinki: Fapet, pp. 55-72.

Krogerus, B., 2007. Papermaking additives. In: R. Alén, ed. *Book 4: Papermaking Chemistry.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 54-121.

Kuusipalo, J., Savolainen, A., Laiho, E. & Penttinen, T., 2008. Extrusion coating and products. In: J. Kuusipalo, ed. *Book 12: Paper and Paperboard Converting.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 108-166.

Laamanen, M. & Lahti, J., 2008. Fibre-based packaging materials. In: J. Kuusipalo, ed. *Book 12: Paper and Paperboard Converting.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 210-242.

Levlin, J.-E., 1983. Tärkeimmät kuituraaka-aineet ja niiden paperitekniset ominaisuudet. In: A. Arjas, ed. *Paperin valmistus, osa 1.* 2nd ed. Helsinki: Suomen Paperi-insinöörien yhdistys, pp. 27-46.

Lipponen, E., 1983. Paperin liimaus. In: A. Arjas, ed. *Paperin valmistus, osa 1.* 2nd ed. Helsinki: Suomen Paperi-insinöörien yhdistys, pp. 289-309.

Lumiainen, J. & Harju, K., 2008. Slushing and defibration of pulp in the paper mill. In: H. Paulapuro, ed. *Book 8, Papermaking part 1, Stock Preparation and Wet End.* Helsinki: Finnish Paper Engineer's Association, pp. 77-91.

Mälkiä, T., 2015. *Kartonkikoneen tuoreveden käytön vähentäminen kemiallisesti puhdistettua jätevesikirkastetta hyödyntäen.* Master's thesis. Lappeenranta: Lappeenrannan teknillinen yliopisto.

Nilsen, H., 1983. Käytetyt vedet. In: A. Arjas, ed. *Paperin valmistus, osa 2.* 2nd ed. Helsinki: Suomen Paperi-insinöörien yhdistys, pp. 921-950.

Norman, B., 2008. Web Forming. In: H. Paulapuro, ed. *Book 8, Papermaking Part 1, Stock Preparation and Wet End.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 218-288.

Nuortila-Jokinen, J., 1995. *The closed paper mill white water system and the internal paper mill white water treatment,* Lappeenranta: Lappeenrannan teknillinen korkekoulu.

Panchapakesan, 1992. White water reuse and savealls. In: M. J. Kocurek, ed. *Pulp and Paper Manufacture: Volume 6, Stock preparation.* 3rd ed. Atlanta, GA, USA / Montreal, Que., Canada: The Joint Textbook Committee of the paper industry TAPPI & CPPA, pp. 173-186.

Pöyry, 2014. *KA4 tuoreveden käytön vähentäminen. Prosessiselvitysraportti.* [Online] Available at: Stora Enso Intranet [Accessed 26 2 2021].

Smook, G. A., 2016. *Handbook for Pulp & Paper Technologists.* 4th ed. Peachtree Corners, GA: TAPPI PRESS.

Stetter, A., 2006a. Systems for Fiber Stock Preparation. In: H. Holik, ed. *Handbook of Paper and Board.* Weinheim: WILEY-VCH, pp. 194-207.

Stetter, A., 2006b. Water circuits. In: H. Holik, ed. *Handbook of Paper and Board.* Weinheim: Wiley-VCH, pp. 208-218.

Stora Enso, 2015a. *Käyttöohje KÄO RPO 01 Raakaveden pumppaus.* [Online] Available at: Stora Enso Intranet [Accessed 13 4 2021].

Stora Enso, 2015b. *Käyttöohje KÄO ST2 02 ST2 toimintakuvaus.* [Online] Available at: Stora Enso Intranet [Accessed 14 4 2021].

Stora Enso, 2020. *Käytttöohje KÄO RVP 02 RVP Toimintakuvaus.* [Online] Available at: Stora Enso Intranet [Accessed 14 4 2021].

Stora Enso, 2021a. *Imatran tehtaiden esitysaineisto.* [Online] Available at: Stora Enso intranet
[Accessed 15 1 2021].

Stora Enso, 2021b. *Imatra mills 2020. Presentation material.* [Online] Available at: Stora Enso Intranet
[Accessed 26 1 2021].

Stora Enso, 2021c. *Ajo-ohje AJO KA4 100.* [Online] Available at: Stora Enso intranet
[Accessed 14 4 2021].

Stora Enso, 2021d. *Imatran tehtaiden tuotanto.* [Online] Available at: Stora Enso Intranet
[Accessed 15 4 2021].

Suhr, M. et al., 2015. *Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board.* [Online] Available at: https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/PP_revised_BREF_2015.pdf
[Accessed 26 4 2021].

Sundholm, P., 2008. Mill operations in the production of main paper and board grades - an overview. In: H. Paulapuro, ed. *Book 8: Papermaking Part 1, Stock Preparation and Wet End.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 9-60.

Thomas, F. E., 1992. Broke system design. In: M. J. Kocurek, ed. *Pulp and Paper Manufacture: Volume 6, Stock preparation.* 3rd ed. Atlanta, GA, USA / Montreal, Que., Canada: The Joint Textbook Committee of the Paper Industry TAPPI & CPPA, pp. 161-172.

Trimble Inc., 2021. *Wedge in brief.* [Online] Available at: https://wedge.trimble.com
[Accessed 19 4 2021].

Valmet, 2021a. *Distributed Control System.* [Online] Available at: https://www.valmet.com/automation/distributed-control-system/ [Accessed 18 3 2021].

Valmet, 2021b. *Valmet Fiber Image Analyzer.* [Online] Available at: https://www.valmet.com/automation/analyzers-measurements/analyzers/fiber-image-analyzer-for-external-fibrillation-fiber-length-measurement/
[Accessed 8 4 2021].

Weise, U., Terho, J. & Paulapuro, H., 2008. Stock and water systems of the paper machine. In: H. Paulapuro, ed. *Book 8, Papermaking part 1, Stock Preparation and Wet End.* 2nd ed. Helsinki: Finnish Paper Engineers' Association, pp. 140-216.

Table I. Solids content measurements from super clear filtrate.

Date	Time	Solids content, mg/L	Valve opening, %	Washing time, s	Break time, min
9.3.2021	8:03	5.2	16.0	45.0	3.4
9.3.2021	9:00	5.0	16.0	45.0	3.4
9.3.2021	10:00	7.9	16.0	45.0	3.4
9.3.2021	13:43	11.5	17.0	45.0	3.4
9.3.2021	13:44	9.9	17.0	45.0	3.4
10.3.2021	8:06	1.0	16.0	45.0	3.4
10.3.2021	8:07	1.4	16.0	45.0	3.4
10.3.2021	12:11	1.1	17.0	60.0	3.4
10.3.2021	12:12	1.9	17.0	60.0	3.4
10.3.2021	16:00	1.5	18.0	60.0	3.4
10.3.2021	16:01	1.8	18.0	60.0	3.4
11.3.2021	8:03	1.5	16.0	45.0	3.4
11.3.2021	8:04	3.6	16.0	45.0	3.4
11.3.2021	10:32	4.4	19.0	60.0	3.4
11.3.2021	10:33	4.5	19.0	60.0	3.4
11.3.2021	12:28	8.0	19.0	60.0	3.4
11.3.2021	12:29	7.2	19.0	60.0	3.4
11.3.2021	14:57	3.7	19.0	60.0	3.4
11.3.2021	14:58	4.9	19.0	60.0	3.4
11.3.2021	16:51	4.8	16.0	45.0	3.4
11.3.2021	16:52	5.8	16.0	45.0	3.4
12.3.2021	7:52	1.2	16.0	45.0	3.4
12.3.2021	7:53	1.9	16.0	45.0	3.4
12.3.2021	10:09	4.9	19.0	30.0	2.0
12.3.2021	10:10	8.6	19.0	30.0	2.0
12.3.2021	12:05	8.3	19.0	45.0	2.0
12.3.2021	12:06	6.4	19.0	45.0	2.0
12.3.2021	13:58	0.0	19.0	45.0	2.0
12.3.2021	13:59	0.0	19.0	45.0	2.0
12.3.2021	16:09	2.9	20.0	45.0	2.0
12.3.2021	16:10	1.8	20.0	45.0	2.0

Table II. Solids content measurements from shower water tank water.

Date	Time	Solids content, mg/L	Valve opening, %	Washing time, s	Break time, min
9.3.2021	8:07	3.3	16.0	45.0	3.4
9.3.2021	9:03	5.2	16.0	45.0	3.4
9.3.2021	10:04	4.5	16.0	45.0	3.4
9.3.2021	13:47	10.4	17.0	45.0	3.4
9.3.2021	13:48	8.0	17.0	45.0	3.4
10.3.2021	8:10	0.1	16.0	45.0	3.4
10.3.2021	8:11	0.0	16.0	45.0	3.4
10.3.2021	12:15	0.1	17.0	60.0	3.4
10.3.2021	12:16	0.3	17.0	60.0	3.4
10.3.2021	16:05	3.5	18.0	60.0	3.4
10.3.2021	16:06	1.6	18.0	60.0	3.4
11.3.2021	8:06	1.4	16.0	45.0	3.4
11.3.2021	8:07	1.9	16.0	45.0	3.4
11.3.2021	10:35	1.5	19.0	60.0	3.4
11.3.2021	10:36	2.4	19.0	60.0	3.4
11.3.2021	12:32	6.1	19.0	60.0	3.4
11.3.2021	12:33	6.5	19.0	60.0	3.4
11.3.2021	15:01	1.1	19.0	60.0	3.4
11.3.2021	15:02	0.9	19.0	60.0	3.4
11.3.2021	16:54	3.1	16.0	45.0	3.4
11.3.2021	16:55	1.7	16.0	45.0	3.4
12.3.2021	7:56	2.4	16.0	45.0	3.4
12.3.2021	7:57	2.4	16.0	45.0	3.4
12.3.2021	10:13	6.2	19.0	30.0	2.0
12.3.2021	10:14	3.6	19.0	30.0	2.0
12.3.2021	12:08	6.1	19.0	45.0	2.0
12.3.2021	12:09	0.3	19.0	45.0	2.0
12.3.2021	14:01	0.0	19.0	45.0	2.0
12.3.2021	14:02	0.0	19.0	45.0	2.0
12.3.2021	16:12	1.7	20.0	45.0	2.0
12.3.2021	16:13	1.9	20.0	45.0	2.0