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Refining Energy and Chemical Savings in the BCTMP-process

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ABSTRACT

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Refining Energy and Chemical Savings in the BCTMP-Process

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The purpose of this thesis was to reduce the amount of operating costs of a BCTMP mill. The authors aim was to gather information about the process and locate the parts where the mill was producing qualitythat was well-above the customer standards.

The data were collected from the mechanical pulp mill using the mill DCS system with a two-hour interval from a two-week period in both refining and bleaching departments. The Data was modelled with the regression tool in Excel to find possible savings mechanisms from the mill processes via correlation and causality research.

The results were that the energy consumption of the BCTMP process was high and it was possible to decrease the average refining energy by 54 kWh/adt. This combined with the possibility to save 3 kg/ton on peroxide consumption would lead up to 700 000 € total savings per year with the reported production rate, energy price and chemical price.

This study leads to academic discussion for additional operational savings in mills that are already operating based on the mill data. When mills find these topics interesting, further studies for cost savings will be to analyse the water removal efficiency in the process by optimising the different dryers in the process and eventually optimising the press and drying sections of paper machines for the most cost efficient water removal. In chemical pulping, further studies could include saving energy by minimising cooking temperature and optimising the average Kappa-level to make the process more stable.

Key words: BCTMP, pulp, mechanical pulping, refining, bleaching, paper, board, analytics, regression analysis, data, linear regression

Contents

ABBREVIATIONS

BCTMP	bleached chemithermomechanical pulp
CMP	chemimechanical pulp
CV	coefficient of variation
CSF	Canadian Standard Freeness
CTMP	chemithermomechanical pulp
DTPA	diethylene triamine penta-acetic acid
DTPMPA	diethylene triamine pentamethylene phosfonic acid
DCS	distributed control system
EDTA	ethylene diamine tetra-acetic acid
H2O2	hydrogen peroxide
H2SO4	sulfuric acid
HC	high consistency
ISO %	European measuring standard for brightness
LC	Low consistency
NaOH	sodium hydroxide
PGW	pressure groundwood
RPM	rotations per minute
SEC	specific energy consumption
TMP	thermomechanical pulp

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1. INTRODUCTION

1.1 Research topic

The research topic was chosen by the current need in mill organization to study mechanical pulping process and the potential savings that might be found from it. Researcher has also interest in the topic and has been working with BCTMP – process before. Mechanical pulping process is very different from chemical pulping process, leading to very different pulp properties in the end product. The pulp properties and manufacturing methods must be studied before any savings mechanisms can be targeted from the process.

Mechanical pulp mills are constructed all around the world and the usage of mechanical pulp is growing rapidly. This trend is ongoing mainly because the current need for fiber-based products is optimal for mechanical pulping. Compared to chemical pulp, it is cheaper, and still has very good strength properties and in some mills, it has been possible to completely stop the usage of kraft-fiber.

Because mechanical pulp is processed with large refiners, the energy consumption is also very big, this of course means that the potential savings are also large even though the average amount of refining energy used for pulp ton has come down in the recent years. The amount of bleaching chemicals is also a topic of interest, since it is hard to determine how much bleaching chemicals in the process is exactly enough. Mills usually end up using more bleaching chemicals than they need.

Compared to chemical pulp production, mechanical pulping has challenges with the lignin remaining in the pulp. When left in the wood lignin guarantees a high yield, even over 90 % but reduces the brightness. For bleaching the most used method is the oxidizing peroxide bleaching in two stages. However, peroxide lowers bulk properties so other bleaching methods are also considered in the industry.

BCTMP – process uses a lot of energy and chemicals. Mills have been eager to find ways to decrease the costs while still maintaining the same level of quality for their end-product. Because the mill operations are not always running very smoothly it is hard to gain reliable data from a longer period of time to really figure out how the process could be operated at the most economically viable way. In many cases the most important thing for the mill day-to-day operations management is just to keep the production rolling even if it would sometimes require excessive energy and chemical usage. In this thesis the mill's operating targets are analyzed, and new possible targets are determined for the mills without reducing the customers quality targets but only affecting the cost structure of the mill.

Part of the research was also to discuss about the change management for the mill employees after the potential savings methods had been found and correct measures decided on how to achieve those savings. How to not only make the change happen, but also make the change last.

1.2 Research Questions

The aim of this thesis is to study the topics of BCTMP - mill production technology, possible bottle necks in the process and potential ways to improve already well working processes. After the process research is done, the research goal converts to finding an efficient way to bring the savings to the mill floor. This would consist of organizational restructuring, employee training and making the change cultural, not only organizational. This would mean that the change would last, and the employees would adopt it as their way to operate in the mill. The objective of this thesis is to understand the impact of BCTMP-process into the fibers and to study the effectiveness of different processes to the virgin fiber.

The purpose of this research is to look the process as a whole, but with also bringing the human element into the equation. It is possible to achieve the savings in the paper by calculating process parameters, but to get the whole organization to follow the managements needs is different. It is important to recognize how the changes are experienced, how the upcoming challenges can be handled and how the mill can be not only more productive, but more transparent place to work. The results can be used to focus the resources to the target areas, where the saving potentials are the biggest and where the most improvement can be done with the smallest effort.

The main research questions are:

How can we achieve savings in refining energy in mechanical pulping?

How can we achieve savings in chemical consumption in mechanical pulp bleaching?

How can we manage the organizational change and make it last?

The first and second questions aim specifically for answering the main research topic: is it possible to achieve savings in the BCTMP – process. The third question mainly focuses on how the theoretical savings can be implemented in the mill environment to achieve the savings also in the site. Not to only have the savings potential calculated, but to have the employees motivated of doing so and have a positive impact on the work culture.

1.3 Research approach

The research was formed around process and laboratory data gathered from a BCTMP-mill DCS – system. The purpose of the data is to keep the mill operators, supervisors and management aware of the mill situation regarding, production, quality and maintenance. From the mill data it is possible to draw graphs and provide the mill employees deeper understanding of what really is happening in the mill processes. When looking for two week data period, it is possible to see also different operating targets since the mill is producing one grade at a time for a couple of days before switching into another one. In this data set we have data from two grades that have different brightness targets. From that data it is possible to see, how changes in refining energy or chemical dosing are affecting the end pulp qualities. When looking the mill data as a whole, it also makes the employees better understand their responsibilities, they see what is usually wrong with the product and how they can improve it. Their knowledge about their job and tasks increases.

1.4 Data analysis

The data is laboratory data and data gathered from Mill DCS system from a two week – period and gathered by a mill engineer from the mill DCS-system into an excel-file. Analytics phase was started with filtering the data was to obtain as normal process operating parameters as possible. After filtering, it was possible to form graphs from the data and analyze the averages, standard deviations and coefficient of variables from the data. This was done with the basic excel tools. After this, the data mining could start and it was possible to see what the standard level for SEC and ISO % - brightness were and how did they compare with the high- and low-limits of the values. This part also requires understanding of the BCTMP-mill process, not only about the data analysis.

From the mill data, it is possible to acknowledge how much energy refining consumes and when also having the pricing information of the energy used, it is possible to calculate the savings and the optimal price for the final freeness target of the pulp. Same model was applied to bleaching as well. When the amount of peroxide used and how much it costs is combined with the information of final brightness, it is possible to calculate how much the peroxide is bleaching the pulp and if the dosage could be reduced. The purpose of the linear regression analysis is to check the coefficients of each of the variables, in this case for example SEC and freeness and declare the relationship between variables more specifically.

Ultimately the target was to check from the data if they are refining too much and is the mill bleaching too much. From there it would be possible to calculate how much the mill could save by using less energy and less bleaching chemicals. In order to be able to reliably calculate these savings, the data must be filtered at first. This means that the possible process downtimes are not taken account in the process study because they don’t represent the process accurately. Also from the data must be filtered out the machinery breakdowns, that tilt the process balance too much to one way or another. For example if one refiner drops out, the others can pick up the workload but for the accuracy of the data it is better to leave those parts out of the calculation. All the data used is constantly available in the mill DCS and is logged into the mill history database and it is collected every other hour, so it is possible to have an hourly data from the process. The data was collected by a fiber analyzer. The results from the linear regression can ideally provide new information of the variable relations. Purpose of the data analysis with linear regression is to detect how selected data of the pulp mill affects selected variables. Data analysis of the data can provide knowledge about selected variable and what effect it has to other dedicated data variables.

1.5 Structure of thesis

This thesis is structured in a following way:

Chapter 2. Theory about wood species and their differences. How the differences in wood species affect different pulping and papermaking processes, including BCTMP-process.

Chapter 3. Theory of mechanical pulping, including the mechanical pulping methods, different process stages of mechanical pulping and theory about refining. How different refiners are structured and what is their operating principles, how the fiber is affected by the BCTMP-process and how the fiber is treated after refining, including screening, latency removal and reject handling.

Chapter 4. Theory of bleaching in mechanical pulping, how different bleaching chemicals affect the pulp and what kind of reactions happen during the bleaching process. What kind of dosing is suitable for different chemicals and what kind of exposure times and temperatures should be used in the process. Drying and baling are also discussed.

Chapter 5. Theory of pulp properties in BCTMP – process. What are the most important optical and strength properties to achieve when manufacturing the end product. Also other properties and their importance are discussed, as bulk, freeness and fiber length.

Chapter 6. Theory about making the change in the mill site. What are the key dimensions to focus when planning the change and how the change can be prepared with precise steps in the pre-change phase. Latter part of the chapter is reserved for discussing about the upkeep, how to make the change last and a summary of the literature of the thesis.

Chapter 7. Experimental part, synthesis and methodology of the linear regression. How the data analysis was made and what was found. How the energy and chemical consumption have been calculated and modelled and how the savings can be deduced.

Chapter 8. Result part, viewing the results and discussing what the results mean, what are the next steps for the mill and what should be studied next.

2. WOOD SPECIES

In BCTMP – process not only softwood can be used, but also hardwood species as raw material. Wood material and its chemical composition are the most essential factors in the production of mechanical pulp. The morphology and mechanical properties of the fibers affect the mechanical defibering energy consumption and the characteristics of the pulp product. The chemical composition of wood directly affects certain properties of the pulp, such as brightness and strength properties as well as the whole process stability. (Varhimo, Sirviö & Tuovinen 2009, 70).

Wood is a very heterogenous material and between different tree species there can occur big differences regarding the chemical composition affecting the quality of the mechanical pulp. In its basic form wood consists of rather long cells that vary a lot depending on their form and function. Lignin makes the wood species distinguishable from herbaceous species. When fiber wall contains lignin, it is wooden and for example bamboo is a herbaceous plant despite its size. (Kärkkäinen 2003, 15) These cells are usually called as fibers. The most important components of the fiber are lignin, cellulose and hemicellulose. Additionally, the fiber includes wood extracts depending on the wood specie in question. (Häggblom-Ahnger & Komulainen 2005, 24)

The out layer of fiber is called the primary wall, inside the primary wall there is a three-layered secondary wall and the main material these walls consist is cellulose. Cellulose is the most important part of the fibers and it enables their use in paper production, but as it is also an insoluble substance the cellulose is hard to separate from the wood in pure form because its close integration with lignin and hemicellulose. (Pettersen 1984, 121) Hemicellulose attaches fibers into each other and also lignin attaches the fibers tightly into one another and gives stiffness. (Häggblom-Ahnger & Komulainen 2005, 25) Figure 1 shows the structure of fiber.

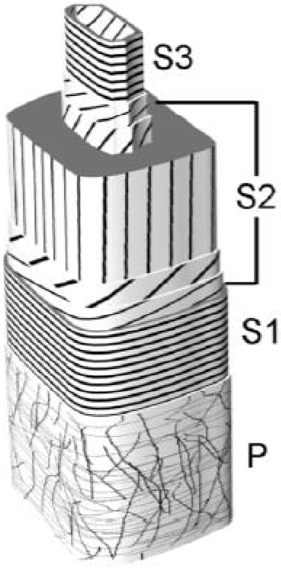


FIGURE 1 Wood fiber cellular wall structure (Brändström 2002, 45)

2.1 Wood properties

Differences in the structure of softwood and hardwood are important for mechanical pulping. Looking at the whole, deciduous trees have a more complex physical structure than with conifers and in mechanical pulping softwood have been the most used species. Spruce brings low extract – content, and even extracts only make up only up to 5 % of wood, they have a significant effect to wood properties, like durability and colour. (Pensar 1977, 186.) Spruce also has good fiber properties and high starting brightness. Fiber length and width are affected by the age of the wood and the location of fiber in the log. (Seppälä, et al. 2001, 24-28)

Wood density is important for the economical side, paper mills buy the wood by the volume and the higher the density, higher the yield. Almost all wood species have the same density in the fiber wall, but the thickness varies. Dense and heavy wood has thick fiber walls and small cell cavities. (Koponen 1998, 52) Moisture content is in this case important and the moisture content of wood is obtained by dividing the mass of water in the wood by the wood by the total dry weight and multiplying the result by 100. (Glass & Zelinka 2010, 4-1)

Adequate moisture content of wood is an important factor in the production of mechanical pulp. Together with temperature, moisture content is essential when softening wood lignin and it differs a lot between the heart of the tree and the surface layers of the tree. Salmen (2007, 22) acknowledges that the moisture difference can be as big as 40 % between different layers of the wood. Wood is also hygroscopic material, meaning that it sucks moisture from air to itself. The moisture merges first to the fiber walls and from that the water will start to storage into the cell cavities. Wood material also varies in size depending on the humidity, the cell walls either fill with water (adsorption) or release water (desorption). (Kärkkäinen 2003, 175)

2.2 Chemical composition of wood

Two groups can be acknowledged from the wood-species, hardwood and softwood from where softwoods are gymnosperm trees and hardwoods are angiosperm trees. (Stenius 2000) Additionally, the wood contains varying amounts of pectin, starch and proteins and low molecular weight components such as extracts, water-soluble organic compounds as well as inorganic compounds, but mainly it consists of carbohydrates (cellulose and hemicelluloses) and lignin as seen in table 1. (Sjöström & Westermark 1999, 8) The chemical composition also varies within wood in different parts when comparing trunk tree to branches, canopy and roots.

TABLE 1. Typical chemical composition of wood (Alén 2000, 16)

Chemical component	**% of dry matter**
Carbohydrates	65 - 80
Cellulose	40 - 45
Hemicellulose	25 - 35
Lignin	20 - 30
Extracts	2 - 5
Proteins	< 0,5
Inorganic substances	0,1 – 1
SiO_2	<0,1

2.2.1 Cellulose

From the carbohydrates, the cellulose is the main substance and it's share of the dry-weight of the wood is 40 %. It is also the most common biopolymer in the world. Cellulose molecules are located mainly in the fibers secondary wall. They form hydrogen bonds with neighboring molecules and give the wood cell the mechanical support structure and the fibers a good tensile strength. (Sjöström 1978 55-56.) Figure 2 illustrates the structure of cellulose.

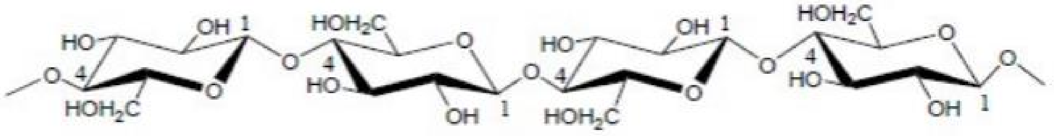


FIGURE 2. Stereochemical structure of cellulose (Alen 2000, 34)

The structure of cellulose is linear, which can be seen in Picture 2 (Alen 2000, 34) that depicts the molecule structure. Molecules have been formed by glucose units that have been engaged. Each unit of glucopyranose contains three hydroxyl groups (-OH) through which the polymer has a strong tendency to form internal and external hydrogen bonds in the molecule. The degree of polymerization is in the order of 10 000, but the number can vary between different parts of the tree and different cell layers. (Jääskeläinen & Sundqvist 2007, 65-67.) The degree of polymerization can be reduced to the order of 1000 in bleached kraft pulps as in industrial use the main products are cardboard and paper, including derivative products like cellophane and rayon. (Nishiyama, Langan & Chanzy 2002, 31)

Hydrogen bonds are formed inside the cellulose molecule and between molecules. These cellulose molecules form molecular bundles and due to this commitment to the cellulose molecular bundles aggregate into microfibrils, which can form both crystalline and amorphous regions. The vast majority of these regions are crystalline and most of the non-crystalline cellulose is accessible to micro-organisms and water, but part of it is covered with lignin and hemicellulose which makes the cellulose non-accessible. This accessibility is important for pulping, chemical modification and moisturizing. (Rowell 2012, 36) As microfibrils continue to combine into fibrils and cellulose fibers a high degree of crystallinity (60-75 %) characteristic of cellulose is formed, which makes the polymer chemically very stable material as well as increases the tensile strength of the pulp. This means that cellulose is very insoluble regarding water, but with few chemicals it is possible to penetrate the crystallized regions, leading to the swelling of crystallization and bringing the reagent closer to the hydroxyl groups leading to the growth of insolution. (Jääskeläinen & Sundqvist 2007 67-72.)

2.2.2 Hemicelluloses

Hemicelluloses contain typically 20-35 % of the woods dry-weight and they control the water content of the cellular walls. Softwood and hardwood have different structure and composition of hemicellulose, but both are colorless and stable compounds. They also consist the same amount of sugars and different parts of the wood are characterized by the relationships between different saccharide units. (Manasrah 2009, 9) Hemicelluloses are heteropolysaccharides that have a low degree of polymerization (100-200), they consist of pentoses, hexoses or deoxyhexose. These structures may have small amounts of uronic acids. These units make up the hemicelluloses components such as the deciduous glucomannans and glucuronixylans or conifer galactoglucomannans and arabinoglucuroxylans. (Sjöström & Westermark 1999, 1-19) Figure 3 illustrates the hemicellulose structures of softwood and hardwood.

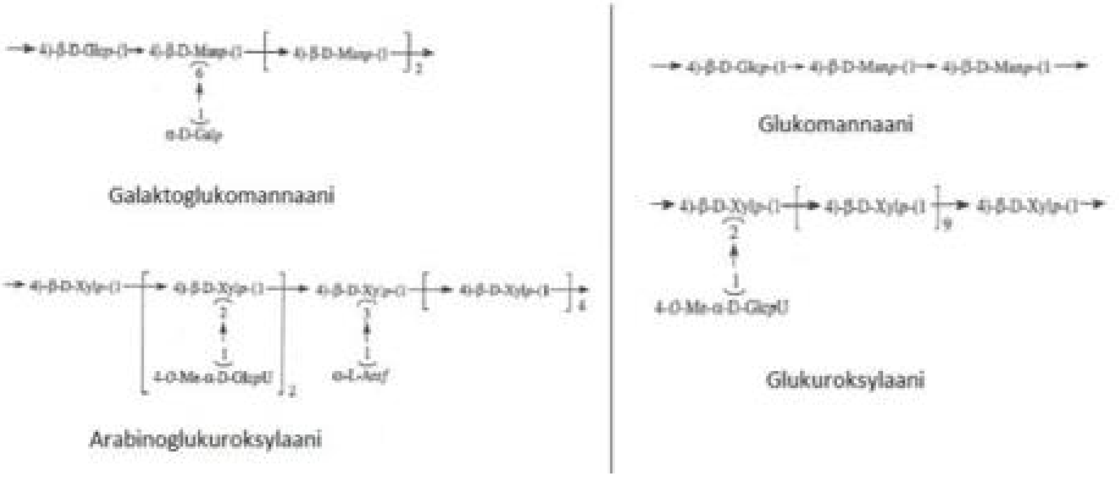


FIGURE 3. Softwood (left) and hardwood (right) hemicellulose structure (Alen 2000, 38)

Hemicelluloses are chemically and thermally more unstable than cellulose. This is caused by the branched and amorphous structure of hemicelluloses as well as the low degree of polymerization. Hemicelluloses are located in cell walls of the fibers where they act as wall support materials. They form internal bonds in the wood with lignin and cellulose, and they can also be isolated from wood by extraction with a neutral or alkaline solvent. (Sjöström 1993, 58)

2.2.3 Lignin

Lignin consistency in softwood is typically between 26-32 % and in hardwood 18-26 %. In softwood, over 70 % of lignin is located in the secondary layer of the cellular wall. Lignin differs from other macromolecules of wood significantly, it is an amorphous polymer and its function is to support the structure of the wood by filling the carbohydrate backbone intermediate lamella vacuums. The branched and reticulated structure of lignin consists of three different aromatic phenylpropane unit. (Sjöström 1993, 61) Structural units present in the structure of lignin, from the left trans-coniferyl alcohol, trans-sinapyl alcohol and trans-p-coumaryl alcohol. In figure 4, it is possible to see the structural units of lignin.

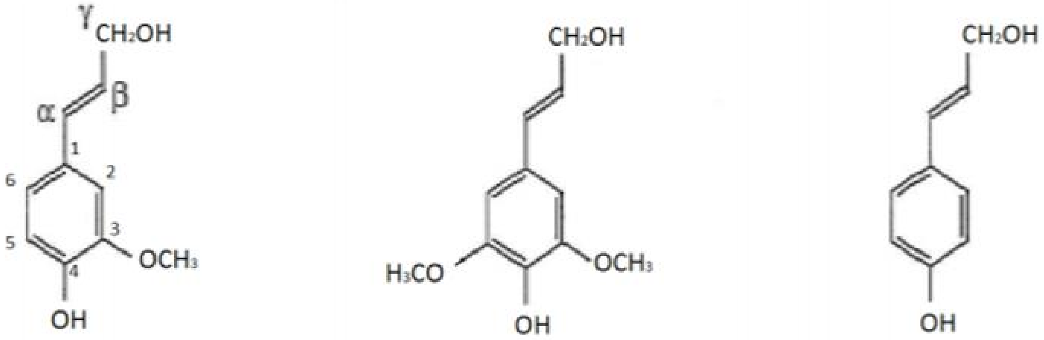


FIGURE 4. Structural units occurring in the structure of lignin (Alen 2000, 40)

Lignin resides as part of the lignocellulosic matrix where the cellulose is surrounded by a monolayer of hemicellulose and embedded in a matrix of lignin and hemicellulose. Lignin creates a barrier to enzymatic attack when in the same time the crystalline structure of cellulose is insoluble in water, after that the hemicellulose and lignin create a protective sheath around the cellulose. (Stenius 2000, 121) The structural units of lignin are joined together by ether bonds or carbon-carbon bonds, bonds also occur between lignin units and hemicelluloses. Information about the exact structure of the bond type is important when considering lignin degradation reactions in manufacturing or bleaching wood pulp. As a polymer, the chemical structure of lignin is extremely irregular because the structural units bind to each other in many different ways. Most of the lignin is located in the secondary layer of the cell walls, but its concentration is the highest in the intermediate lamella. Lignin is sparingly soluble in common solvents, which makes it a hard to study. Acid hydrolysis of carbohydrates has proven to be the best way to separate lignin from wood residue. (Sjöström 1978, 91-92.)

2.2.4 Extractives

Extractants are heterogeneous low molecular weight compounds in wood, which are generally soluble in neutral organic solvents and water. Largest extractant concentrations in wood are usually found in bark and heartwood. Residues like bark remain very attractive sources of bioactive molecules as bark is usually considered a low-value by product that used to only hold value for its energy potential. Bark generally contains a high concentration of extractives with very good economic properties in biological industry. (Royer, Houdem, Viano & Stevanovic 2012, 3).

Chemically extractives can be divided into alcohols, aldehydes and ketones, acids, resin acids, carbohydrates, phenol, nitric compounds and hydrocarbons that exist mainly as terpenes. (Azarov, Burov & Obolenskaya 1999, 626)

Extracts can be divided aliphatic, phenolic and other compounds. The compounds may be lipophilic and / or hydrophilic and are considered non-structural in wood as substances. Conifers contain resin compounds that are purely lipophilic compounds and they can be separated from the wood only with non-polar organic solvents. In the tree extractors affect the color, smell and taste of wood and some of them can act on wood cells as an energy source for its activities. Resin compounds also protect wood from microbiological damage as well as from insects. There are considerable differences between extractives in hardwoods and softwoods extending to different tree species. The resin acids occur only in softwoods and the amount of resin varies a lot between species. Fatty acid composition also differs between species and also between softwood and hardwood. (Holmbom 1999, 126)

In the manufacture of pulp, extractants are not desirable compounds because they can cause precipitates and impurities in the pulp, leading to quality problems in the final product. (Alén & Selin 2007, 166)

2.2.5 Inorganic compounds

The amounts of inorganic substances found in wood are quite low, usually 0.3 - 1.5 % of wood depending on the total dry matter of the tree where it is grown and the climatic conditions. Inorganic substances are important for the growth of wood, they are found most in leaves and needles, but they also occurs in the bark of the tree. Inorganic substances are determined using wood ash atomic absorption spectroscopy. The most abundant substance in ash are calcium, potassium and magnesium, which cover almost 80 % of the inorganic content of conifers and deciduous trees material. (Sjöström 1993, 94) There are also small concentrations of other inorganic compounds in the wood such manganese, sodium, phosphorus and iron. Separating these substances from wood by washing is difficult, the washed pulp contains almost as much inorganic matter as the raw wood material. In total, wood contains dozens of different inorganic compounds. (Jääskeläinen & Sundqvist 2007.)

In the manufacturing of wood pulp inorganic substances and especially metals cause the breakdown of carbohydrates as well as problems with brightness. Because of this metals are sought to be separated from the pulp in the process by the use of chelating agents for the purpose for example ethylenediaminetetraacetic acid (EDTA) or diethylenetriaminepentaacetic acid (DTPA). (Sjöström 1978, 94-95.)

3 MECHANICAL PULPING

Mechanical pulp is usually produced out of chipped wood in either one or two refining stages. Debarked and chipped wood is inserted between refiners segments where the woodchips eventually fibrillate to single fibers by heat and mechanical stress. Before refining the chips have been softened by chemicals and steam heating.

Raw material is usually softwood, especially spruce and in premium TMP-grades the pulp is usually bleached before usage. Bleaching is usually done with peroxide and dithionite.

3.1 Mechanical pulping methods

3.1.1 Thermo-mechanical pulping

In TMP the chips are heated before the actual refining process, in the heating-phase the lignin in the fiber is softened to help the fibers detach from each other and so that the fibers would keep their size and form better. The heating of the wood chips happens either in atmospheric pressure or in a pressurized chamber. The heating last 2-5 minutes and the pressure in the pre-heating is 0,5-1 bar. Higher preheating temperature increases strength-properties and lower preheating temperature is better for optical properties. In pressurized preheating the chipped wood is fed to the first stage refiner with 3-5 bar overpressure and 140-155 - degree temperature. After the first stage the refined pulp is blown with steam to another refiner with similar pressure and temperature. The steam is captured and the pulp is directed to main- and reject line before the paper machine.

3.1.2 Chemithermomechanical pulp, CTMP

Production of CTMP differentiates from the TMP-production by the chemical pretreatment of the wood chips. It is meant to soften the fibers before the actual refining process. Typically, the chemical treatment increases the fibrillization, leading to lower stick level with less refining. Typical chemicals used are sodium sulfate, sodium hydroxide and some cases hydrogen peroxide. Chemical treatment of woodchips has made possible hardwood usage in thermo-mechanical pulping. It also made possible more unique pulp types for different paper grades.

3.1.3 Bleached chemithermomechanical pulp, BCTMP

Next stage is to add bleaching into the mechanical pulp manufacturing, this is called BCTMP. After refining the ISO % - brightness is typically between 60-65 %. Mechanically refined pulp has better light scattering properties than chemical pulp. The most significant factors affecting light scattering and opacity are the amount of optically active fines as well as the partially opened and externally strongly fibrillated fibers. The cell walls of the fibers and structures are damaged in mechanical refining increasing the surface area of the fiber and this reducing the amount of light entering the fiber. In addition the formed fines and the external fibrillation of the fiber create bonds between the fibers that block the passage of light. As the light refracting interfaces increases in the paper layer, light scattering also increases. (Braaten 2000, 124)

BCTMP is mainly used in products where mechanical pulp does not have the quality properties, but where chemical pulp is too expensive and good. For example cardboard production is a big consumer of BCTMP.

3.2 Production of BCTMP

Usually the raw material of BCTMP is made in the mill site, meaning that the mill does not buy the woodchips from f. ex. a nearby sawmill, but they need a debarking, chipping and chip screening processes. After chipping, the chips are stored either into storage silos or into the chip field, which means that the chips are laying in the outside unprotected and it gets affected by dirt and different weather conditions. Chip drying in the summer and chip freezing in the winter have an impact to the process stability and the pulp quality. (Sirviö & Tuominen 2009, 70-74.) When producing BCTMP, the mechanical defibering of the wood is combined with chemical pretreatment. With the chemical usage it is possible to enhance the softening of the lignin in the interlayer and fibrillation of the wood, this leads to more desirable properties for paper and board making in the pulp. The main benefit for BCTMP is high bulk, that leads to the ability to produce stiffer but in the same time lighter board compared to only chemical pulp. Additional benefits include good absorption properties and low manufacturing costs. (Klinga, Höglund & Sandberg 2008, 99)

3.2.1 Peeling, chipping and screening

In the manufacturing process of the BCTMP, bark significantly reduces the brightness of the pulp and therefore it should be avoided. Bark also does not help with the strength properties and with large extractant content the yield can suffer from high bark content. (Kappel 1999, 34)

In the debarking process, the conveyor directs trees to debarking drums with a diameter of 4,0 – 6,0 m and length 18 - 40 meters. The debarking drums operating principle is that the trees rotate against the walls and against each other leading to the detaching of bark from the wood surface. Peeling is aimed to perform so efficiently, that adequate chip purity is achieved while in the same time minimizing the amount of wood leaving the bark. After the debarking process the wood trunks are directed to chipping where the most important thing is to prepare the chips of the highest possible quality and uniform in size distribution. Formation of sticks and fines is minimal with modern chipping machinery. The amount of approved wood chips can be controlled by the cutting geometry and the dimensions of the cutting blade. (Kappel 1999, 35)

Directing the chips through sieves with different dimensions, the desired size distribution is achieved. Approved wood chips may not exceed 45 mm in any direction and in addition the chips must be thinner than 7 mm as seen in table 2. If the chips are too fine, they can cause yield losses as well as pulp quality deterioration. In the pulp, the fines have negative effect especially to the strength properties, but they increase the brightness, opacity and light scattering properties of the pulp. This process leads also the increase of stick number. If the chips are too large, the energy consumption is increased in order to able to achieve the same level of freeness (Canadian Standard Freeness, CSF) as with approved chip size. Oversized chips also shorten the length of the fibers, and in addition, the strength and brightness of the pulp suffer. From the chip pockets the chips are transported to the BCTMP-plant, the purpose of chip screening is to separate the oversized fractions and return them back to sorting after being crushed to smaller chips. (Seppälä, Klemetti & Kortelainen 2005, 60)

TABLE 2. Chip sieve dimensions (Kappel 1999, 34)

Sieve	**Chip attached to the sieve**
>45mm holes	Oversized chips
45mm holes – 7mm gaps	Thick chips
7mm gaps – 7mm holes	Accepted chips
7mm holes – 3mm holes	Stick chips
<3mm holes	Fines

Generally, wood chips are stored, in which case the shelf life of BCTMP should be as short as possible. Storing the chips for a too long time can lead to losses in wood via biodegradation which leads to poorer pulp quality, especially in terms of brightness. However, longer storage has a beneficial effect on the amount of wood extractants because they decrease significantly as storage time increases. Storage can be done in chip heaps in the open air or in separate silos. Silo storage can reduce storage adverse effects on pulp quality.

3.2.2 Woodchip heating and washing

From storage silos, wood chips are transported along a conveyor belt towards the process itself. (Tienvieri, Huusari, Sundholm, Vuorio, Kortelainen, Nystedt, Artamo & Loisa 2009, 163) In countries that have winter condition, warm steam can be directed to the conveyor belt to keep the chips warm before washing. Heating the chips with steam at this stage can also facilitate the wetting of the chips as well as raise the temperature itself in the washing phase.

From the conveyor belt, the chips continue to the washing phase comprising the chip washer and water separator in the same water cyclation. The impeller in the washer feeds clean and floating chips in the chip pump feed chute. Large and heavy material drips onto the bottom of the chip washer including saw dust, sand, rocks and heavier metallic compounds. If these impurities would continue to the latter part of the process, they could damage the refining machinery and effect negatively to the product quality. (Jussila, Tienvieri & Sundholm 2009, 425) The impurities are then taken for waste treatment.

The mixture of wood chips and hot water flows at levelled consistency out of the scrubber from which the chip pump transports it to the water separation screw. Drying section may include multiple water separation screws to enhance drying. The chip washing also removes sand, metals, sawdust and bark from the chips. Washing can also have a positive effect to the moisture content of the chips and the increase the temperature of the chips. Water used in the washer is removed from the chips into a wash water tank from which it can be used from where it can be used in the process again after being cleaned. The wash water can be very dirty after the cycle and has been found in it significantly lipophilic extracts, lignans, lignin and total organic carbon. (Seppälä et al. 2005, 62)

3.2.3 Evaporation and impregnation of wood chips

The chips are conveyed by a screw conveyor to a unpressured or pressurized preheater in which 100 - 120 ° C steam is directed between the chips. (Tienvieri et al. 2009, 182) In pressurized steam, the chips are heated for 1 to 10 minutes at a pressure of 100 to 200 kPa. The purpose of steaming is to remove as much air as possible from the chips with water and steam, leading to as complete absorption solution penetration as possible. With steaming it is possible to raise and level moisture content of the chips as well as softening them. From steaming, the chips continue to be absorbed using the plug screw.

The addition of chemicals to the chips can be done at several different points in the process. (El-Sakhawy 2005, 419) It has been found that the addition of chemicals have a positive efficiency of mechanical pulp production, providing better strength properties to the pulp and reduces the energy requirement of the process. In BCTMP manufacturing, the most common step to add chemicals into the process is in between chip washing and refining. (Kappel 1999, 36)

Several different chemicals with several different amounts can be used in the impregnation stage of BCTMP production. The most common chemical used in softwood impregnation is sodium sulfite and most common chemical for hardwood is sodium hydroxide. Other impregnation chemicals that can be used in a mix with sodium sulfite and sodium hydroxide are oxidized green liquor and oxidized white liquor. Hydrogen peroxide can also be used in the impregnation absorption phase, where an even higher brightness is already achieved before refining. In addition, the absorption solution contains water, which is often 0.5 - 1.0 m^3 per ton of pulp. (Tienvieri et al. 2009, 184)

In the BCTMP process, the natrium sulfite dose for softwood impregnation is typically 2-4 % of the dry matter of the wood. natrium hydroxide added at 0 - 0.5 % to adjust the pH-level of the chips. Pre-treated warm chips are soaked in the liquid in a separate soaking tank for 2 to 30 minutes at a 80-120° C temperature, in overpressure. When producing BCTMP from hardwood, the natrium sulfite dose remains very similar, but natrium hydroxide is added to adjust the pH a bit more (1 - 5 %). The steam in the wood chips condenses under the by the effect of cool absorbing liquid, creating vacuum conditions in the chips resulting the absorption liquid flow into the chips. (Leask 1987,101).

It is also possible to carry out the impregnation with the pre-treated chips being mechanically pressed with a plug screw before adding the impregnation solution. The water leaving the pores is then replaced by an impregnation solution and the impregnation takes place more evenly. Other possible impregnation methods are spraying chemicals directly into the chips and the addition of chemicals directly to the refiner. The penetration and diffusion of impregnation should be carried out as completely as possible in order to achieve the desired chemical reactions in the treated wood pulp. (Konn 2006, 77)

In penetration method, the impregnating chemical flows into the wood externally by the effect of pressure when the diffusion is movement of ions into and out of the chips with the effect of concentration differences. Compared to thermomechanical pulp, in impregnation it is possible to obtain longer fibers, less fines and less sticks with the same amount of energy used for refining. (Klinga et al. 2008, 103)

3.2.4 Sulfonation

If the mill has the sulfonation process available, it enables the possibility to get the lignin to swell and soften, allowing the wood structure to be mechanically decompose into a fibrous form. Chemical changes take place in the structure of wood also with lignin, and that is called sulfonation. Sulfonation decomposes the ether bond structure in lignin. (Konn 2006, 78) The sulfonation of BCTMP also affects the softening temperature of the lignin structure. Sulfonation lowers the middle lamella and raises the softening temperature of the primary wall as it produces hydrophilic sulfonic acid groups that improve the solubility of lignin. (Alén 2011, 307)

3.2.5 Refining

Refining is the most important aspect when considering BCTMP process related to the altered behavior of the wood fibers. (Lönnberg 2009, 319) In the refining process the washed wood chips are refined into finished mechanical pulp. The chips are fed between the refining segments, where it is first refined into smaller stick-like pieces, from that into fiber flocks and further into individual fibers. The properties of the mechanical pulp are depending from the energy used for refining and the conditions of the refining. The basic mechanism for fiber detachment is leading various fast stress pulses into the wood material and the basic principle of refining is to separate the fibers from the softened wood as intact as possible without damaging the fibers. (Konn 2006, 80)

In wood chip fibrillation and fiber refining the chips fibrillate and the fibers modify into shape by the compression- and refining forces. Compression forces cause the fibers wood content to heat up and loosening the structure. Refining forces break the wood material into fiber flocks and further into single fibers. Refining phase shapes the fibers as their elasticity and fibering increase, surface area grows and their ability to commit increases. The refining can be performed in one or multiple steps depending on the desired CSF-level. With single stage refining, higher bulk and strength properties are achieved with higher freeness (400-500 ml. But with more refining steps, it is possible to achieve better optical and surface properties with CSF-level of 100-150 mL.(Tienvieri et al. 2009, 193)

3.2.6 Monitoring and controlling refining

The aim of refiner control is to try to keep the refining parameters and factors as constant as possible. Changes in the process that cannot be factored, can be measured and issue them with controls. This requires that the changes affecting the quality of the pulp are well-known. For this to happen the information should be gathered as precisely as possible. There is a lot of inadequacy of information regarding for example the raw materials, refiner segment condition, specific energy consumption and refining consistency. The most important parameter is however the right grindstone selection and optimizing the conditions of refining for the critical factors. (Lönnberg 2009, 408)

Refining result depends from the quality of fiber, amount of refining, refining model and process conditions. For the refiner feed the goal is to keep the quality of the woodchip as constant as possible and the quality parameters in refiners are the ratio of wood species, moisture of wood chips, fraction size, temperature, density variation and timber chip dosing. The amount of refining depends of the production driven through the refiner and the refining power used. High-freeness mechanical pulp is usually refined in a high, over 40 % consistency to save the fiber length. The refining can be controlled by blade gaps, dilution water, consistency and specific energy consumption, the final control parameters depend on the end quality properties. (Lindholm, Nickull & Pitkänen 2009, 261)

Refining model also has big impact to the produced fiber material. High intensity, brute refining produces pulp with low permeability with lower specific energy consumption. This comes with decreasing of fiber length and tear strength. By monitoring the fiber length, it is possible to obtain the exact intensity wanted. The refining model is affected by the amount of refining, process conditions and the model of refining segment. The refining segment edges width, area groove depth and width will vary heavily depending on the end product and the process. (Tienvieri et al., 2009, 204) .

Refining consistency is controlled by adding dilution water. Normally the consistency in the refining zone is about 40-50 % in the first refining stage and 5 % smaller in the second refining stage. Usually the low lewel of refining is 25 % consistency. Refining conditions lower than this have decrease in strength properties and increase in sticks. stage (Mannström 1977, 230)

3.2.7 LC Refining

Low Consistency (LC)-refiners are nowadays in heavy use in BCTMP-mills, they can be located in several different stages of the process. The refining is done in significantly lower consistency than traditionally and in LC-refining it is usually 3-5 %.LC-refining aims to improve especially the printability properties of the pulp and in mechanical pulping LC-refining aims to improve the internal bonds of the fiber formation, refining produces mechanical forces that change and disintegrate fiber structure further, eventually resulting in external and internal fibrillization and release of fines. Refining also reduces the stick content and the amount of coarse fibers in the pulp, amount of latency is removed and the fibers remain longer. The refined fibers give a smoother end product. (Pitkänen et al. 2009, 406)

3.3 Refining behavior of fiber walls

The fiber wall of wood consists of layers consisting of outdoor lamella, primary wall, the outer, middle and inner layers of the secondary wall (S1 to S3) and the nodule layer (W). The layer in the between has the highest lignin content and this layer connects the adjacent fibers together. (Ilvessalo-Pfäffli 1977, 31)

Refining leads to several different structural changes in the fiber wall structure due to the complexity of the fiber wall structure. In the initial stage of refining, the primary film is removed from the fiber, the film prevents the fiber from swelling and does not form bonds with nearby fibers with. As the primary film is detaching, the secondary wall of the fiber appears below leading to the outermost layer S1 beginning to peel off quickly. As the refining is continued, parts also begin to detach from the S2 wall. The layers detach in a plate-like manner without causing external wall fibrillation because of the effect of transverse organization of microfibrils. (Ebeling, Levlin & Nordman 1977, 216)

The loosening of the internal structure of the fiber as a result of refining is called internal fibrillation. It means that the hydrogen bridges between the hydroxyl groups of the chain molecules open and are replaced by hydrogen bridges between chain molecules and water molecules, resulting to swelling of the fiber in water. Internal fibrillation makes the fiber flexible, resulting the fibers adapting to each other’s shapes, the interfaces between the fibers are large and between the fibers bond formation is good. Loosening and breaking of the structure of the fiber surface layer is called external fibrillation. Loosening can only take place in the fiber after the top layers have come off. In external fibrillation of the surface layer the microfibril bundles come off partially and the fibrous surface forms as if hairy. This as a result, the outer surface of the fiber increases and allows the formation of bonds between the fibers. Traditionally the fiber formation is considered based mainly for the formation of hydrogen bonds, but also van der Waals interaction energies have been found to have a significant effect. Especially in the amount of bonds formed in the fiber network. (Knowpap 2018)

As a result of refining, there is always some breakage of the fibers. If the number of broken fibers is too large, it affects negatively the strength properties of the board made from the pulp. In general, the rougher the refining, the more fibers are broken. With BCTMP chemical treatment it is possible to minimize breakage by weakening the inter-fiber bonds in the septum. When manufacturing BCTMP, the fibers almost always come off the septum leaving the number of fines low. However, it is important that the chemicals have time to act sufficiently in the chips before refining. Otherwise, the desired reactions do not occur and softening is not achieved. In the preparation of TMP, the lignin of the interlayer is softened with raising the temperature in which case the detachment of the fibers takes place mainly at the intermediate lamella. This results in long fibers and very little fines. (Ebeling et al 1977, 216)

3.4 Refining energy and feed consistency

The feed consistency of the pulp going to the refiner has a large effect on the steam generated during refining formation the higher the refining consistency, the more steam will be produced. Refining can be performed at high consistency, in which case increasing the consistency from, for example, 35 % to 50 % would increase steam generation by up to 25 %. In the beginning of refining the suspensions of chips and water are transported into the refiner with a feed screw and directed to flow between blades rotating in opposite direction. This is the extreme condition where the refining phenomena occurs and the suspension discharges into the refiner hatch. (Jussila, Tienvieri & Sundholm 2009, 427) Today, the refining trend is towards lower energy consumption for which the consistency has been considerably lowered. Feed consistency also affects the distance between the refiner plates and it has a considerable effect to the pulp quality. It would therefore be a good idea to keep the feed consistency as uniform as possible. (Tienvieri et al. 2009, 196)

Large refiners generate up to 20 tons / hour of steam. Steam pushes the pulp forward by which the common phase proceeds into steam separation cones in which steam and pulp are separated. Effective separation guarantees stable and trouble-free refining process. In case of large vapor generation, pressures may rise to high levels, making it possible for the pressure to push the steam back to the refiner. Therefore, there must be a stopper valve between the refiner and the steam separation cone which prevents steam from returning. The resulting steam is recovered for further use, for example directed into the refiners or for use in the drying section as heat. (Tienvieri et al. 2009, 197)

3.5 Behavior of extracts

Concentrations of extractants in wood are generally less than 5 %, but concentrations vary widely between different parts of the tree, tree species, habitats and tree individuals. Extracts in the coniferous tree are found mainly in resin ducts, nuclear beam parenchymal cells, and heartwood. In deciduous trees extractants are found mainly in parenchymal cells of nuclear rays. With refining, it is possible to affect the amount of extractants in addition to softening the lignin. Parenchymal cells of the wood in which the extracts are largely located are then deleted. During refining 2-5 % of the wood material dissolves or disperses into the process water as colloidal particles. In two-stage refining, most of the soluble and dispersible material is removed immediately during the first refining stage. In a process with additional refining stages the amount of extractants and lignin increase rapidly during the process. The released extractants can be washed from the process, the main washing efficiency controls are the dilution / precipitation rate and process conditions such as pH and temperature. (Manner, Reponen, Holmbom, Kurdin & Pajula 2009, 434)

3.6 Refiner structure and work principle

Disc refiners with two refining segments are mostly used in refining. The refining segments are casted and then inserted into each other. In refining the installation is targeted with great forces, so the installation is required to have sturdy structure especially from axels, frame and bearings. Build material is usually rustproof and acid-proof materials. The blade gap must be controlled and at least the other one of the blade segments must be controllable. Depending on the product quality, there are one or more refiners in series in the refining line and after that possibly few reject refiners to reduce the amount of sticks that have gone through the mainline refiners. (Jussila, Tienvieri & Sundholm 2009, 427)

3.6.1 Single Disk refiner

Single Disk refiner is the simplest disk refiner that has one spinning segment (rotor) and one solid (stator). The blade gap is if necessary controlled by moving the spinning segment. The wood chips are fed to the process through the hub in the middle of the solid segment. Single disk refiners can have a diameter of 1,8 meters at maximum. Refiners that have larger diameters have too big centrifugal force for the structure. (Seppälä 1988, 2) The rotation speed vary between 1000 rpm and 2300 rpm depending on the size of the refiner. Single disk refiners have only one motor, that power depends of the size of the refiner, the biggest ones are 20 MW. Typically, one refining line has two refiners connected in series and reject is directed to its own refiner. Capacity for this kind of refiner line is about 250 tons per day.

3.6.2 Double Disk refiner

Double disk refiner is formed by two refining segments rotating to opposing directions. Both segments are moved by their own motors. Typically the summarized power in the biggest refiners is about 30 MW. Compared to single disk refiner, the amount of impacts to the fibers is double. The wood chips are fed to the segment gap by the segment intervals. The segments are controlled by moving the disc without the hub in the middle. DD-refiner rotation speeds are naturally considerably bigger than SD-refiners, at their highest even 3600 rpm (2 x 1800 rpm). The refining segment diameters are of the same size with the other refiner types. When operating a Double Disk refiner it is also possible to execute the refining in only one stage, for example refining the mechanical pulp to make newsprint paper. The refiner consumes approximately 15 % less energy compared 1500 rpm DD-refiner to 1500 rpm SD-refiner when the freeness target is the same. DD-refined mechanical pulp the fiber length is a bit shorter and light scattering factor is a little bit bigger compared to SD-refined mechanical pulp. Seppälä 2005, 68)

3.6.3 Conical Disk refiner

Conical disk refiner was developed to raise the refining segments size despite the huge centrifugal forces. These are nowadays the main type of refiners in the market. The refiner segment sizes are over 2 meters and motor loads are over 30 MW. The refiner is based on SD-refiner, that has been added a cone-segment. In CD-refiner the blade segment and the conical segment gaps can be separately controlled. With this refining method the produced fiber has a little bit longer fibers.CD-refiner also consumes more energy than the traditional refiners which is caused by the larger refining surface. (Koskenhely 2007, 11)

3.6.4 Twin flow refiner

Twin-refiner is different from a CD-refiner by having only the conical part. This solution has the benefit of larger segment surface area and more precise and easier controllability of the refiner gap. In the refiner the segment disk is rotating between two solid segments forming two separate refining zones and maximizing the production. With twin-refiners it is possible to produce up to 550 tons of TMP per day when refining at 1800 rpm. In twin flow refining, the softwood is refined in 3,5-4,5 % and hardwood fibers are refined in 4,5-5,0 %. (Lumiainen 2000, 106)

3.7 Refiner segments

Refining segments are the most important part of the mechanical pulping process. They have the biggest impact for the properties and quality of the mechanical pulp. The refining segment consists of separate blade blocks and as a whole the refining segment can be divided into three different parts. The center disk, inner blade and outer blade. The surface of the segment consists of blade brushes and blade slots. The blades have crushing zone, conical zone and planar zone with different size gaps. (Metsäteollisuusliitto 1981, 61-63)

With refiner segments it is possible to control the steam and pulp flow in the segment slots and also to the fibrillation and refining event. Segment design is aiming to impact the driving properties of the refiners, energy consumption and the quality of mechanical pulp. For example high refining brushes and deep slots hasten the pulps residence time in the segment gap, low segment gaps in the other hand force the pulp more effectively into the segment gap and increase the residence time. (Lumiainen 2000, 114)

Wide segment gap increases the steam extraction and reduce the quality of the mechanical pulp, narrow segment gaps increase the quality of pulp, but decrease steam extraction and in general level the segment gap dams are used to control the pulp and steam streams but excessive “damning” reduces steam extraction. Then when going deeper into the details, with selective slotting it is possible to increase operating the process and steam extraction and by manipulating the tooth angle, it is possible to control the residence time and steam flow in different zones. With the tooth angle manipulation it is also possible to control the refiner so that it does not brake the fibers, choosing the right kind of blade pattern depends on the refined pulp, what is the end product and what kind of conditions the refining is conducted on. (Lumiainen 2000, 115)

Steel segments vary a lot in different production units, because different mills need different kind of pulp to make sure that runnability and quality properties would be at the best possible level. First and second stage refining and reject refining also need an individual solution if the target is to obtain the optimal result.

3.7.1 Material of the refiner segments

Refining segments should endure a great amount of chemical and mechanical stress. This sets great demands for the wanted segment – materials. Good endurance is achieved by using steel alloys with varied carbon amount. Usually the carbon amount varies between 0,5-1 %. Chrome is used mainly as binder materials for steel alloys, but also nickel, molybdenum and titanium. Nowadays the segment durability is about 1500-3000 hours depending on the type of mechanical pulp and the purity of the pulp. Dimensional variations in blade geometry have increased because of advances in laser- and material technology. Nowadays it is common, that the material is designed and adapted to the process conditions. (Koskenhely 2007, 128)

3.7.2 Low Energy – segments

Low energy – segments were developed to reduce the energy consumption of the refining process. LE-segments targets to reduce the pulp flow residence time in the blades and due that reduce the specific energy consumption of the refining process. Typically, the usage of LE-segments can lead up to 20 % less energy consumption than pulp refined with standard refining segments.

Quality properties are very close to standard segments quality, when targeting the same freeness – value, the fiber length gets little bit shorter but the stick content decreases. Stretch and tensile strength are on par, but tear strength goes down a bit. Optical properties are even better than with standard segments. If needed, it is possible to increase the fiber length by increasing the pressure, this results in decreasing the brightness of the pulp, For example when comparing low energy segments to standard segment in a SD-65 type SD-refiner, LE-segment had a production rate of 2,3 kg/s with 9,2 MW of power consumption, when the standard segments had 2,43 kg/s with 9,7 MW of power consumption. SEC was the same in both. (Illikainen 2008, 45)

3.7.3 Turbine – segment

Traditionally refiner segments have been developed from experience and by trial and error. Turbine – segments are based on modelling the segments to assure the optimization of material- and steam flows. The process temperature is considerably lower with turbine segments compared to other segments which leads to lower specific energy consumption. Lower temperature also increases the optical properties by a lot, even so much that some mills have been able to stop bleaching the pulp completely. Strength properties are not in the same level with standard and LE-segments, but optical properties are better and energy consumption smaller. (Vuorio & Bergqvist 2003, 19)

3.8 Screening and post handling of mechanical pulp

The screening usually does not have to have coarse screening because of the lower stick content. The mechanical pulp is screened by using pressure screener which have the basic functionality based on profiled slit plate that is a bit different for every pulp depending on the quality and purity of the pulp. Modern pressure screeners have made possible to abandon the use of vortex cleaners.

3.9 Post – treatment

Finishing includes post-refining latency removal, pulp sorting and cleaning, treatment of reject streams, bleaching of pulp, drying the pulp and baling. After the treatments BCTMP is ready to be transported to the customer for the manufacturing of the final product.

3.10 Latency removal

At high temperatures, lignin softens and after refining the fibers start to curl. As the pulp cools the curl becomes permanent, this phenomenon can occur in all mechanical pulps due to the high lignin content of raw material. The curled fibers affect the properties of the pulp, increasing CSF, decreasing strength properties and reducing the sorting efficiency of the fibers. The formation of the fibers are dependent on the intensity of the mechanical refining process, the changes in fibers occur in fibre surface change, fibre length change and fibre morphology change. (Page 1989, 32) Therefore, before sorting latency removal must be done, where the fiber curls open and the separation efficiency of the coarse fibers and sticks is improved. The latency is removed in a latency removal tank where the pulp is mixed at low consistency (2-4 %) and high temperature (70-80° C). In the latency removal tank the pulp is mixed with propeller mixer in the tank. In the latency removal tank curling eliminates fibers, in which case the previously changed properties of the pulp also return. (Tienvieri et al. 2009, 199)

3.11 Sorting and cleaning

In the sorting phase BCTMP no longer contains large amounts of chips and sticks. BCTMP compared to TMP contains 30-80 % less sticks due to its chemical stage. However, pulp contains more long and coarse fibers, leading larger amounts of unapproved fractions in the process. The purpose of sorting is to remove unwanted particles from the BCTMP to maintain quality without affecting the runnability of the machine. (Hautala, Hourula, Jussila, Pitkänen, Niinimäki, Jokinen, Leppinen & Ämmälä 2009, 284).

The pulp is directed through the main line sorting through pressure sieves at a pressure of ~ 200 kPa, and the accept continues to the next process stage. The sieve screen drum has holes or slits and the sorter must have a rotor that holds clean the screen surface to prevent clogging. Sticks and unbreakable fiber bundles (reject) are guided by a rotor from the surface of the sieve to the reject process. The reject would cause quality problems if they would end up in the final product, so they are refined again and directed to the same circulation with the accept. Having multiple washing and screening stages within the process is recommended, because the impurities will reduce the end quality, cause damage to machinery and decrease the runnability. The shives originate mostly from processing early wood and in groundwood pulp when processing latewood. (Gregersen 1998, 76)

For post-sorting pulp cleaning, BCTMP mills use cyclones, with cleaning efficiency based on particle separation with gravity. Sticks, coarse fibers and any sticks are removed from the process as well as residues of sand and metals, which in the case of BCTMP are very small. The low consistency pulp (0.3 to 1,5 %) is fed to a cyclone where the pulp is subjected to strong rotational motion. (Gullichsen & Fogelholm 1999, 134) The rotational motion forms a so-called air core in the middle of the cyclone, which allows light fibers (accept) to move forward in the process. Heavier fractions of the pulp descend along the walls of the cyclone, ending in the reject part of the process. The pulp is controlled from the screen through cleaning to pulp precipitation on a disc precipitator, washing press or for a double wire press intended to increase the pulp in a certain volume. The precipitated pulp is directed to a pulp tower, from where it continues to bleaching. Pressure screeners pump the pulp into them, where it uses the pressure differences effect to go through the slit plate. The energy usage is optimized by using feed pumps that have stepless rpm-control. (Gullichsen & Fogelholm 1999, 135)

In pressure screening the best result will come from continuous control and control measurements. In practice the factors that contribute to the end result are pulp input pressure in the sieve, pulp consistency, pressure difference between input and accept, reject ratio and reject dilution, rotor rpm and production capacity. The most important pressure screening factor is the pulp consistency. If the pulp has a high consistency, it is much harder to clean efficiently, when the reject ratio increases to unnecessary high level.

Reject pulp coming from screening is directed to the reject refining, first the pulp must be precipitated. Pre precipitation happens in the arc sieves which bring the consistency up to 3-4 %. The arc sieves also remove the fines from the pulp, which is beneficial regarding the refining process itself. The main precipitators used are disc filters and various presses that bring the consistency over 30 %. It is also possible to reject the so called “light reject”, meaning that it is possible to remove dense than fiber – particles from the pulp, like plastics. These are only a very low portion of the total pulp flow. (Seppälä et al 2005, 51)

Reject refiners are very similar compared to mainline refiners, only the segment surface structure is different. After refining the pulp is directed to pressure screeners and to production, Typically, the reject line pulp is better than the pulp from the mainline, especially regarding the fibers ability to commit.

3.12 Reject handling

In screening the reject that is separated contains sticks and long fibers that are not acceptable to proceed to bleaching. Certain methods are usually used to process reject, such as refining the reject in a separate refiner, adding the reject to the main pulp and refining them together or adding chemicals to the reject. The process is designed to remove coarse particles, improve fiber properties, maintain fines content, maintain fiber length and control pulp dewatering properties. The most common way to process reject is for it to have its own cycle and tank, where the reject is collected from the main line refining. (Huusari, Lundin & Vuorio 2009, 330)

Reject with high CSF the water is usually removed with screw presses at atmospheric pressure. There may be several screw clamps one after another to achieve the desired consistency before refining. From there, the reject continues to reject refining using very similar refiners as the main line refiners. A single plate refiner with stator and rotor is a the most common method. Refining can be done at low consistency (LC, 3-5 %), medium consistency (MC,10-15 %) or at high consistency (HC, 30-50 %). Especially with BCTMP LC-refining is used because of low operating costs, good stick removal efficiency and low energy consumption. LC-refining is however, known to cause shearing in the fibers meaning formation of short fibers. In a modern process it is no longer a desirable feature, because the length of long softwood fibers is preferred over the strength of the paper. (Paulapuro 2008, 64)

Some mills treat the reject chemically in order to achieve better fiber handling or energy savings from refining, for example by sulfonation or alkaline peroxide in order to achieve better fiber handling as well as energy savings from refining.

The chemical treatment has further effects, such as loss of bulk and opacity of the final product due to which the use has not increased. (Jussila, Tienvieri & Sundholm 2009, 420)

The refined pulp continues to vapor separation, which is done in a cyclone or in a steam separator. There is also latency in the refined reject, so the material from the refiner should be directed to the tank where the latency removal takes place. The temperature in the tank should be above 65 ° C and combined with 8 - 22 minutes stay time, the latency is removed from the fibers. From here the refined reject pulp continues to sorting and vortex cleaning, which further separates accept into the main cycle and the remaining reject into a new reject cycle. (Huusari, Lundin & Vuorio 2009, 331)

4 BLEACHING OF MECHANICAL PULP

The purpose of bleaching is to increase the brightness of the pulp. When making mechanical pulp bleaching is done by converting the chromophoric or colored groups of lignin to colorless shape to achieve the desired level of brightness. (Tutus & Usta 2004, 142) Additionally also the colorless phenolic groups of lignin can form colored structures as the temperature increases, wood extractants can also have an effect on fiber discoloration. (Jäkärä, Persson, Mårtens 2007, 368)

This leads to high yield compared to chemical pulping, but brightness is several levels lower. In high yield pulps the bleaching can have also secondary effects in addition to bleaching, it can reduce the amount of extractants and also increase pulp strength and fiber bonds. The brightness is measured from the amount of visible light reflecting from the surface of the end product. (Major, Perrier, Gendron & Lupien 2005, 468).

In the bleaching method that saves lignin, the reducing chemical used is sodium bisulfite and sodium dithionite, where the oxygenizing chemical is peroxide. In mechanical pulping, the brightness of the treated pulp after fibering is ISO 50-68 % (Kappel 1999, 41)

Starting brightness is affected by the wood species as seen in table 3, since the dry-content of the wood affects the brightness properties. Warehousing is also affecting the start brightness, in storage the micro-organisms, air, light, temperature and metallics have an effect in the process. One year of storage time has been studied to have 7 % decrease in brightness in the wood content. TMP was mostly affected by moisture, temperature and light, but also the time spent in storage had an effect to the brightness. (Nilsson, Edlund, Elg-Christofferson, Sjöström & Agnemo 2003, 370)

TABLE 3. Unbleached mechanical pulp brightness from different wood species (Dence 1996, 172)

Species	**Brightness ISO %**
Scots Pine	65
Norway spruce	65
Aspen	70
Birch	32 – 50

The most widely used bleaching chemical in mechanical pulps is hydrogen peroxide (H_2O_2). It oxidizes chromophoric groups of lignin while removing their color. With peroxide the process must use also at least NaOH to make the bleaching sufficient. Peroxide as an unstable substance need a stabilizer into its reactions, often using silicates. Bleaching can be performed at low or high density, although a combination of these are used nowadays. Important parameters related to bleaching are also temperature, exposure time and pH as mechanical pulp contains almost all the lignin in the wood. (Polcin & Rapson 1971, 72)

In the BCTMP process, bleaching takes place in separate towers and is usually two-stage (MC + HC). Tower bleaching requires the removal of water and metals before bleaching to prevent peroxide decomposing before bleaching reactions. A blender is also required for tower bleaching mixing the chemicals with the pulp and a tower where the chemicals are given the required exposure time. Bleaching consistency is usually 30-35 %. After each bleaching tower there is also a washing process in which the dissolved and colloidal material (DCS) and the anionic material are washed from the pulp. Washing processes also enable residual peroxide to be recycled and reused in the process. Some mills even use two stage MC + HC bleaching process followed by further treatment with dithionite. It is also possible to use refiner or flake drying bleaching In addition to tower bleaching. There are screw and wire presses between the bleaching and pulp towers to help adjust the consistency of the pulp for each bleaching step. From the last bleached pulp tower the pulp continues through wire presses to drying section. BCTMP can eventually be brightened even to 80 % ISO. When peroxide is used for the pulp, final acidification with bleaching can be performed after bleaching is adjusted to suit. (Knowpap, 2020).

Sulfuric acid (H2SO4) is usually used to acidification. The chemical removes the alkali residue in the pulp and prevents the pulp from darkening after bleaching. In addition to pulp bleaching, peroxide bleaching reduces pulp extractant content, resulting in a cleaner pulp. The alkalinity of the pulp increases the flexibility of the fibers and improves their refining and strength properties. However, raising the brightness lowers opacity and light scattering coefficient value. In reducing bleaching, bisulphite, dithionite or borodydride is used. (Casey 1980, 98)

4.1 Commonly used chemicals

In the bleaching of mechanical pulp the chemicals are mainly peroxide and dithionite, also sodium hydroxide is needed alongside stabilizing chemicals and chelation chemicals.

4.1.1 Peroxide

In peroxide bleaching the most commonly used peroxide is hydrogen peroxide. In bleaching, the significant role is played by perhydroxyl-anion, which is formed in alkalic conditions. Anion is a strong nucleophile that converts electron-containing chromophores into AB-unsaturated aldehydes and ketones and phenolic ring-conjugated ethylene and ketones carbonyl groups as their non-chromophoric counterstructures. As the chromophores oxides to colorless, the pulp brightens. The formation of perhydroxyl ions in bleaching can be increased by increasing the alkalinity of the process, or by increasing the peroxide dose or temperature. If the pH or temperature is raised too much, hydrogen peroxide decomposes into oxygen and water. (Jäkärä et al. 2009, 368)

Lignin reaction with peroxide is non-reversible and results in the persistence of chromophore groups in lignin molecules removal. When adding peroxide, even

1 % dosage increase in relation to the amount of dry-material it is possible to have a noticeable increase into brightness. 3-4 % increase can lead to 15-20 % ISO increase in the brightness. (Presley & Hill 1996, 460)

Important variables in peroxide bleaching are peroxide dosage, total alkalinity, stability of bleaching liquid, consistency, temperature, duration of action and metal-binding chelating agents. General peroxide bleaching conditions are shown in Table 4.

TABLE 4. Standard conditions in peroxide bleaching (Lindholm et al. 2009, 251)

Dosage	1 – 4 %
pH	10,5 - 11,5
Consistency	30 – 35 %
Temperature	70 - 80 °C
Exposure time	2 – 4 h
Additional chemicals	Alkali, stabilizer, chelating agents

4.1.2 Dithionite

Sodium hydrosulfite (Na2S2O4) is generally used bleaching. The compound is a volatile substance that decomposes easily in water and oxidizes immediately in the presence of oxygen. Raising the pH of the solution to 8-10 substantially slows down the decomposition of dithionite, high temperatures also accelerate the decomposition of dithionite and the more concentrated the solution, the faster it decomposes. It will always decompose eventually, so the best way to avoid it is to keep the storage time as short as possible. (Jäkärä et al. 2009, 383) Dithionite reacts with the carbonyl structures of lignin or lignin derivatives found in ortho- and paraquinones and in the side chains of coniferyl aldehyde units. Reduction reactions result in colorless jaw forms of colored chromophores. (Ellis 1996, 492)

4.1.3 Sodium Hydroxide

Sodium hydroxide (NaOH) is needed for the bleaching reaction in peroxide bleaching. The amount of NaOH depends on the peroxide dose used. The higher the peroxide dose, the more NaOH required. Generally the ratio of NaOH to peroxide is about 0,8-1:1 and at the beginning of bleaching the pH is about 11,5. (Jäkärä et al. 2009, 371) The compound also causes the organic matter to dissolve and if the amount of residual peroxide is too low, NaOH causes permanent yellowing. The amount of NaOH should be chosen so that the best balance between bleaching, decomposition and yellowing is achieved. (Kappel 1999, 43)

4.1.4 Stabilizers

In peroxide bleaching, peroxide decomposes by metals before bleaching reaction, which causes an increase in the use of peroxide in the process as well as increased costs for the mill. Peroxide degradation can be prevented by stabilizing the bleaching liquid. The most used stabilizers are silicates, especially sodium silicate (Na2SiO3). Na2SiO3 reduces effectively decomposes peroxide during bleaching, improves the stability of the bleaching fluid, and is an economic option. (Presley & Hill 1996, 462) The actual mechanism of how sodium silicate works is yet unknown, it has been shown that a dose of silicate improves the bleaching result. Mills tend to want to reduce the use of silicate, as it is easily enriched in the process causing for example precipitation and retention deterioration on a paper machine. In current mills the ratio of silicate to hydrogen peroxide in the solution is about 0,6-1:1. (Jäkärä et al. 2009, 374)

4.2 Reactions in Peroxide Bleaching

Hydrogen peroxide is known to decompose through ionization and radical reactions in reactions 1-4 in accordance with:

$$H_2O_2 \leftrightarrow HOO^- + H^+ \quad (1)$$

$$H_2O_2 \rightarrow HO^- + OH^+ \quad (2)$$

$$H_2O_2 \rightarrow HOO^- + H^+ \quad (3)$$

$$H_2O_2 \leftrightarrow HOO^- + H^+ \quad (4)$$

Where H_2O_2 is Hydrogen peroxide, H is Hydrogen, and O is Oxygen. (Presley & Hill 1996, 463)

In alkaline bleaching conditions, the active bleaching component is the perhydroxyl anion HOO−, formed according to reaction 5 by adjusting the pH and temperature of the system. The equilibrium of the reaction is best on the perhydroxyl anion side at pH 10-11 and at higher temperatures (70-80 ° C).

$$H_2O_2 + HO^- \leftrightarrow HOO^- + H_2O \quad (5)$$

Where H_2O is water. (Strunk 1987, 236)

The equilibrium of the reaction is best on the perhydroxyl anion side at pH 10-11 and at higher temperatures (70-80 ° C). Other reactive components present in alkaline peroxide bleaching are formed due to the decomposition of peroxide and the self-oxidation of lignin during bleaching. Such components include molecular oxygen (O2), hydroxyl radicals (HO ·) and superoxide anions (O2 - ·), all of which have only a minor bleaching effect. (Presley & Hill 1996, 463)

Hydrogen peroxide is a rather unstable compound under bleaching conditions, which is easily decomposed by reaction 6. (Presley & Hill 1996, 463)

$$2\ H_2O_2 \text{ -> } O_2 + 2\ H_2O \qquad (6)$$

Degradation is also promoted by the presence of metals such as iron and manganese, which is why bleach uses a stabilizer to prevent decomposition. The metals act as catalysts in peroxide decomposition and cause a chain reaction through radical reactions, as in reactions 7-10, where M is a metal such as iron, manganese or copper. Without chelating agents, heavy metals catalyze the decomposition of peroxide and the pulp darkens. (Seppälä et al. 2005, 54)

$$H_2O_2 + M^{n+} \text{ -> } M^{(n+1)+} + HO^- + HO \qquad (7)$$

$$HOO^- + M^{(n+1)\,+} + OH^- \text{ -> } M^{(n+} + H_2O + O^-{}_2 \qquad (8)$$

$$M^{(n+1)\,+} + O^-{}_2 \text{ -> } O_2 + M^{n+} \qquad (9)$$

$$O^-{}_2 + HO \text{ -> } O_2 + HO^- \qquad (10)$$

Degradation of hydrogen peroxide by metal ions results in a reduction of perhydroxyl ions, which also results in the decrease in conversion of colored chromophore groups to colorless ones. However, the hydroxyl radicals and superoxide ions formed in this case have found to have a brightness-increasing effect on chemi-mechanical pulps bleaching. (Presley & Hill 1996, 464)

4.3 Dosage

Achieving the desired brightness is directly dependent on the amount of peroxide applied in bleaching. Even a peroxide dose of 1 % by pulp per dry matter can increase the brightness by 6 – 8 % ISO. As the dose is increased, the brightness increases simultaneously, with a 4 % dose it is possible get up to 15 – 20 % ISO increase in brightness to the pulp. (Jäkärä et al. 2009, 368) The maximum dose is usually up to 4 % and the operational zone is 0,5-4 % depending on the brightness target. With the peroxide dose is it is also important to monitor other variables such as alkalinity, consistency, temperature and exposure time. They all have a significant effect on dosing efficiency. (Presley & Hill 1996, 465) Figure 5 illustrates the peroxide dosage effect to pulp brightness..

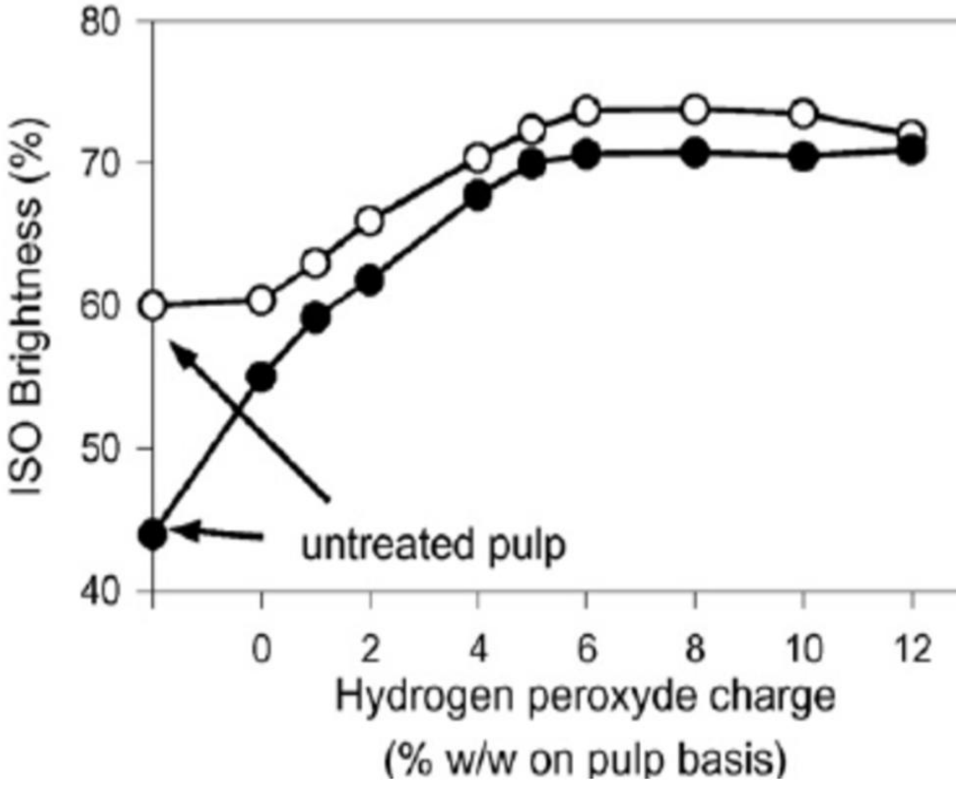


FIGURE 5. Peroxide dosage effect to pulp brightness (Lindholm et al. 2009, 251)

4.4 pH/alkali in Peroxide Bleaching

Peroxide bleaching is performed under alkaline conditions because the presence of hydroxyl ions (HO−) allows the formation of the main bleach component known as perhydroxyl anion. The amount of alkali is an essential variable because too low an alkalinity leads to inefficient bleaching, while excessive alkalinity causes the pulp to darken or turn yellow. Generally the proven initial pH is between 10.5 and 11.5. To achieve the optimal pH is also consider the factor, the higher the peroxide dose, the more alkali is needed. (Presley & Hill 1996, 465) Too high pH must be avoided to avoid the peroxide decomposition reactions. Optimal pH range is mainly determined by the raw material and pulp quality, peroxide dose, consistency, bleach reaction time and depending on the temperature. Also the desired properties of the fibers have an effect on the pH range on the bleaching process, depending what are the preferred end qualities of strength, opacity, or bulk etc. (Jäkärä et al. 2009, 370) Figure 6 illustrates the peroxide and alkali ratio in pulp.

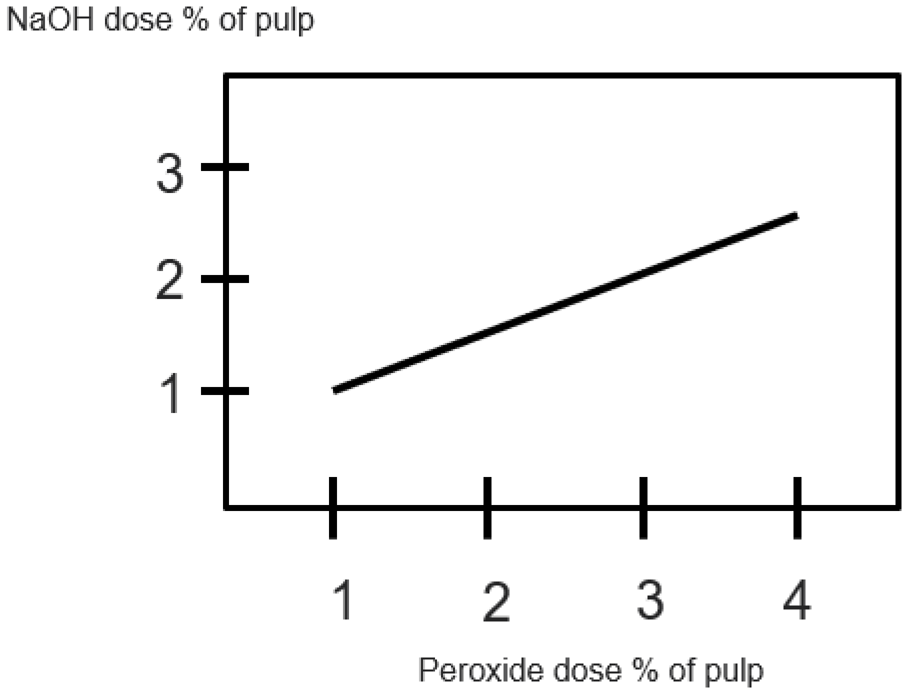


FIGURE 6. Peroxide and alkali ratio in pulp (Pykäläinen, Lehto, & Nyström 1993, 421)

The amount of total alkali (T.A.) is also important in bleaching. It is the sum of all alkaline substances in the bleaching liquid expressed as NaOH. When adding for example sodium silicate ($Na2SiO3$) used in peroxide bleaching, for example as a 41 ° Be solution, the total alkali formula is:

$$\% \text{ total alkali} = \% \text{ NaOH} + 0{,}115 \% \text{ Na}_2\text{SiO}_3 \qquad (11)$$

A workable way to express the amounts of peroxide and total alkali is therefore the ratio T.A./ $H2O2$. The optimum ratio of these decreases as the amount of peroxide increases. (Presley & Hill 1996, 466)

To provide alkalinity, the hydroxyl ion may be derived from compounds other than of NaOH. NaOH is the most commonly used alkali with peroxide, but alternative alkalis to partially or completely replace NaOH include magnesium hydroxide, $Mg (OH) 2$ and calcium hydroxide, $Ca (OH) 2$. (Hietanen & Backfolk 2013, 246)

4.5 Consistency in Peroxide Bleaching

Peroxide bleaching can be performed over a wide consistency range (4 to 35 %), but the general rule is that bleaching is more effective the higher the consistency of the pulp is. As the consistency increases, the hydrogen peroxide concentration in the pulp also increases. This means, that the consistency of the pulp affects both the speed of the bleaching reactions and also to the final brightness of the pulp. The higher consistency also means, that is contains less circulating water, meaning that it contains less waterborne impurities such as heavy metals. (Jäkärä et al. 2009, 375)

In the past decades the consistency has been kept rather low due to equipment limitations (15 – 20 %), but in modern processes it is possible to bleach at high consistency (30 - 35 %). Benefits of higher consistency come from a higher concentration of bleaching liquid and from reduced amount of impurities, leading to faster bleaching reactions. Limitations on consistency are mainly due to the process temperature and the difficulty in causing the bleaching chemicals to mix with the pulp when the consistency is high. It has also been found that lower consistency requires more peroxide to achieve the same brightness as the pulp of higher consistency. Lower consistency pulp also reaches its upper limit more quickly, where there is no more peroxide dose increase benefit in terms of brightness. (Presley & Hill 1996, 467)

4.6 Temperature and exposure time in Peroxide Bleaching

Temperature and exposure have the biggest correlation in peroxide bleaching. When the temperature rises, the bleaching reactions accelerate, shortening the duration of affection time for bleaching liquid. The decomposition of peroxide also increases as the temperature rises and the reactions between the alkali and the pulp are accelerated, causing the pulp to darken. (Casey 1980, 99) The bleaching variables must therefore be chosen so as to achieve the desired brightness at reasonable doses without wasting the chemical and darkening the pulp. Most commonly as seen in table 5, the temperature is between 70 - 80 ° C and exposure time 2 - 4 hours when bleaching at high consistency. (Presley & Hill 1996, 469)

TABLE 5. Temperature, exposure time and alkali ratios in peroxide bleaching process (Lindholm et al. 2009, 252)

Temperature °C	**Exposure time**	**Alkality**
35 – 44	4 – 6 h	medium/high
60 – 79	2 – 3 h	medium
93 – 98	5 – 20 min	low

The dose also matters, as a higher dose of peroxide requires more alkali because higher temperature accelerates the reaction. In this case the consistency of the pulp is forced to decrease or alternatively reduce the amount of alkali. Reduction of alkali leads to increased residual peroxide emergence in the pulp. It is good to leave a small concentration of residual peroxide in the pulp (1/10 of the added peroxide) to prevent the alkali from darkening the pulp, but in excessive amounts the chemical goes to waste. (Jäkärä et all. 2009, 376) Here, the exposure time plays an important role and sufficient time is chosen depending on peroxide dose. Longer exposure time usually results into 1 to 2 % ISO unit higher brightness. (Presley & Hill 1996, 470)

4.7 Residual peroxide in Peroxide Bleaching

If the pulp must be even brighter, peroxide dose has to be raised even higher, up to 4 %. In this case, not all peroxide have the possibility to react with the pulp, even if there is an excess of reaction time. This will lead to surplus amount of residual peroxide in the filtrate water. When the amount of residual peroxide is 5 to 10 kg / metric ton, it is already profitable to wash the peroxide away from bleaching. The filtrate can then be used, for example, for 2-stage peroxide bleaching in medium-density bleaching, resulting in savings on total peroxide consumption. The filtrate can also use 1-stage peroxide bleaching as a pretreatment, which has obtained a brightness increase of about 2 % ISO unit compared to the peroxide-treated pulp in only one stage. (Kappel 1999, 44)

After the washing it is also possible to delete the residual peroxide remaining in the pulp by acidifying it with sulfur dioxide water or alternatively with sulfuric acid. Acidification is especially important before adding dithionite, because if the pulp is not acidified well enough and residual peroxide levels are too high in the pulp, it reduces the bleaching effect of the reducing dithionite. After acidification, the dithionate phase can be performed as tower bleaching. (Jäkärä et al. 2009, 385)

4.8 Bleaching methods in Peroxide Bleaching

When bleaching mechanical high yield pulp with peroxide the most important thing is evenly mixed pulp with a bleaching chemical in well maintained conditions. The most common method of bleaching 2-stage MC/HC – bleaching which is usually performed as tower bleaching. In addition to the tower, bleaching can also be performed as a refining or flake dryer bleach. (Presley & Hill 1996, 470)

In 2-stage MC/HC – bleaching the recipitated pulp is first bleached in MC bleaching, after which the pulp is washed and reprecipitated again before HC bleaching. After HC bleaching the pulp is further washed and dried / precipitated before proceeding. When adding high peroxide doses, more and more residual peroxide remains in the pulp filtrate which has not reacted with the pulp even if the reaction time is sufficient. (Presley & Hill 1996, 471) As an example 1 % peroxide dose usually reacts completely, but increasing the dose up to 4 %, up to 30-40 % of the peroxide will not react with the pulp. Before cleaning the pulp after HC-tower it is possible to recover the residual peroxide filtrate from the presses and recycled to the first stage of bleaching. Due to the recycling of residual peroxide, the consistency of the MC stage bleaching does not increase to the average consistency higher, but the bleaching method still achieves the maximum required of BCTMP brightness by utilizing any possible peroxide that is fed into the process. (Strunk 1987, 234)

4.9 Drying and baling

Usually the mills producing mechanical pulp are located near the papermills and are operating as an integrate. In an integrate the washed pulp is fed to the paper machine by a pipeline and the water is not removed from the pulp. When manufacturing high quality BCTMP the drying of the pulp is more popular, because it makes possible the storing and transporting the pulp more easily. Drying is important because excessive moisture in the end product will lead to spoilage of the pulp and makes the pulp vulnerable to micro-organisms. (Gavelin 1980, 6)

In BCTMP-mills the drying is performed by flake drying, where the waterless pulp coming from wire presses is pressed into a solid fiber carpet with dryness content of 40-50 %. (Kappel 1999, 44) The carpet is broken down to flakes and after that it is directed into hot steam and to flake dryer where the residual moisture is vaporized in seconds. The dried pulp is forwarded into cyclone, where fibers and air is separated. Eventually the dried pulp falls into the bale former, where it is squeezed into disks and the discs are constructed into pulp bales. The bales are weighted, re-squeezed, wrapped into a paper and marked. In BCTMP the individual bales are assembled to large units and wired together to left waiting for the delivery into the next location.

5 PULP PROPERTIES FOR BCTMP

BCTMP is used in various ways, but the most prominent use is in manufacturing of folding boxboard where pulp is used to the middle layer of the multilayer board. BCTMP is most commonly used in liquid packaging cartons where, due to its purity, it does not cause odor and taste nuisances to the product. In multilayer board, the goal of layering is to produce the desired properties at minimum cost. The aim is to make the middle layer as thick and low-density as possible, giving the desired stiffness to the product. BCTMP is also used in tissue paper, in printing and writing papers and, thanks to its absorbent properties, in hygiene products.

The main goal is to produce a board - grade pulp with a solid balance of bulk and peel strength. The biggest challenges are minimizing sticks and ensuring good bonding of the fibers, thus preventing the layers of paperboard from separating and delamination. The properties of BCTMP can be divided into optical properties, strength properties and other properties. (Jussila, Tienvieri & Sundholm 2009, 422)

5.1 Optical properties

The impression of brightness and color in a material depends on the type of light hitting it, the surface reflection properties as well as the sensitivity of the eye to different wavelengths of light. In BCTMP these properties can be measured by looking at the brightness, opacity, color, tones and light scattering and light absorption coefficients. The optical properties are based on the interaction of light and paper. (Häggblom-Ahnger & Komulainen 2005, 99)

5.1.1 Brightness

Brightness measurement was developed to monitor pulp bleaching efficiency. Brightness is defined as a measure of the reflection of blue light on a pulp sheet surface or as opacity from a stack of paper or paperboard. The hue of bleached paper and paperboard is lighter than unbleached because they reflect more of the blue light of the spectrum. The increase in reflection is due to a decrease in the concentration of colored chromophores in the pulp due to the effect of bleaching. Treated chromophores do not absorb light. Most commonly the measurements use a standardized ISO brightness of R457 that has a spectral sensitivity distribution maximum at 457 nm. Pulp bleaching tends to increase reflection at the blue end of the spectrum where the ISO brightness measurement is focused. From here for this reason, the assay is very sensitive to changes in brightness caused by bleaching, which is why the measurement is very effective in monitoring the development of brightness in the bleached pulp. Brightness correlates well with the visual impression, when using optical brighteners Y-value can give deviating values from the brightness impression, so it is always best to measure and not trust your eyes only. (Leskelä 2008, 141)

5.1.2 Opacity

Opacity is the materials ability to prevent light from passing through it, in other words how much you cannot see through from it. Opacity is expressed as a percentage against a black surface as the ratio of the measured reflection number in relation to the limit reflection number. It is essentially associated with a Y-value that indicates the sensitivity of the device to different wavelengths of light so that it corresponds a healthy eyes sensitivity distribution. (Vaarasalo 1999, 164)

$$\text{Opacity} = \left(\frac{Yo}{Y}\right) * 100\% \tag{12}$$

In the equation, Y is the value of Y in the sheet measured at C / 2 ° and Y0 is the value of Y measured in one sheet under the same conditions against a black background. The notation C / 2 ° indicates the standardized method, where the measurement uses C light and a 2 ° standard observer. TAPPI has defined opacity for packaging materials, where 89 % would be the desired value. The higher the opacity value is, the better the material will withstand printing without the ink interfering with, for example on the other side of the carton. The magnitude of the opacity is substantially affected by the light scattering coefficient. When the light scattering coefficient is improved, for example, by lowering the CSF value of the pulp or by using fillers, the opacity can also be increased. Mechanical pulp always has better opacity compared to chemical pulp due to its high light scattering. (Pauler 2012, 153) In the modern times opacity has become an important value, when paper manufacturers are using all options possible to lower the basis weight of the paper. Basis weight should get low, however overprinting should be able to prevent. (Leskelä 2008, 148)

5.1.3 Color / shades

Color perception comes from the combined effect of psychological and physical factors in the observers visual system. Structure of the body and the light source determine how light enters the subject into observers eye and different wavelengths are seen as different colors. (Leskelä 2008, 151) When looking at the color and shade of a material, three factors play a key role. One factor describes the brightness of the color and the other two describe the hues of the color as well as the saturation of the color. The CIE L * a * b * system consists of a gray axis L, a yellow-blue axis b and a green-red axis a. System values a and b can get positive or negative values for it depending on the color of the pulp. Pulp production aims for shades so that L is as close as possible to 100 meaning it is a white as possible. Both a & b prefer slightly negative rather than positive values. (Pauler 2012, 155)

5.1.4 Light scattering and absorption

The larger the surface area on the surface exposed to the light, the more light scattering occurs. The amount of scattering also depends on the surface reflection index. Light absorption measures how much light entering the surface of a material is absorbed into the material and both parameters can be defined by pulp as coefficients. The practical goal is to find out the reflection properties of the pulp with the help of two material constants which, together with the basis weight of the pulp, give the coefficient of reflection against a certain known background. (Pauler 2012, 156)

When manufacturing of mechanical pulp, refining and the amount of fines resulting from it increase light scattering coefficient, allowing the pulp to achieve very similar brightness compared to chemical pulp. Bleaching further reduces light absorption by removing light from the pulp absorbent colored compounds. (Vaarasalo 1999, 165) Light scattering ability makes the paper look brighter and more opaque than if it would be optically homogeneous, because some of the light is reflected back in the incoming direction. This means that the proportion of reflected light increases and the proportion of transmitted light decreases. This is observed as a decrease in opacity when grinding the pulp. When increasing the refining, fiber binding ability improves and decreases the proportion of scattering enabling free surface. Fillers tend to have higher refractive index than fibers and better particle size, so they have a scattering effect leading to improved opacity. (Aaltonen 1983, 231)

5.2 Strength properties

Different customers want different properties from the BCTMP they are purchasing, in general it is possible to say that in the production of board and paper the strength requirements are the most important ones for most of the customers and these include especially peel, tensile and tear strengths. The strength properties are measured by loading the paperboard sample until it breaks and stating the situation at the moment of breaking.

5.2.1 Tensile strength

Tensile strength is the maximum force which a strip of a certain size is able to resist before breaking it parallel to the surface when pulling. The tensile strength is expressed in kN / m, from which tensile strength index can be further calculated for better ability to compare different kind of products. The index relates the force used to measure to the used basis weight. For this reason, the tensile index is a more commonly used parameter to describe pulp strength properties. (Levlin 1999, 139)

$$\text{Tensile strength index (Nm/g)} = \frac{Tensilestrength}{grammage} \qquad (13)$$

The highest tensile strength is obtained with strong and straight fibers, which also have good binding properties. The strength level is determined by the individual fiber and if the fiber is thin or has damaged walls, strength properties remain low. In the production stage structural damage to the fibers easily occur, impacting the strength of the fibers. Adjusting the refining and chemical treatment of the pulp, it is possible to prevent un-needed damage to the fibers in which case the tensile strength will also be better. It is also important to remember, that curled fiber has weaker tensile strength properties than straight fiber. (Metsäteollisuuden Työnantajaliitto 1981, 17)

5.2.2 Tear strength

Tear strength refers to the force that causes a tear of a certain length in a sheet or in a stack of sheets. Strength is highly dependent on the fiber formation value in the sheet. The tear strength is expressed in N or mN and the tear strength index can be calculated by a formula below. The index again relates the force applied to the basis weight used for the measurement. When at first increasing refining, the tear strength increases, but after a while it starts to decrease. Some pulps don't have the increasing tear strength period in the beginning, but it only decreases when increasing refining. (Häggblom-Ahnger. & Komulainen 2006, 98)

$$\text{Tear strengh index (mN * m}^2\text{/g)} = \frac{Tearstrength}{grammage} \quad (14)$$

At the point of tearing, some of the fibers break and some of the fibers have been pulled out intact. The work required for tearing consists of work done pulling out the fibers that have remained intact during tearing and work done to cut broken fibers. Factors affecting to the pullout force for the intact fibers are the force needed to break the bonds and the friction resisting the initial pulling. In mechanical pulping, refining first increases the tear strength, but as refining continues, the strength also decreases as the fibers weaken. The higher the tear strength goes, the more the tear pulls intact fibers out of each side and the longer the pulled fibers are. (Levlin, 1999, 140)

5.2.3 Peel strength

Peels strength is measured either by Scott Bond or Z-strength measurement. Peel strength is defined as work per unit area of the sheet on which the specimen strip is peeled to the tensile load in perpendicular fashion. Fragmentation of different layers in the sample are called ply bonds meaning the interlayer strength. The internal bond describes the strength inside the layer. When strength between layers is greater than the internal strength of the weaker layer, the paperboard of the different layer cracks inside the weaker layer. (KnowPap, 2018)

The bonding ability of the fibers has a large effect on the peel strength. The importance of binding ability is greater the shorter the fibers are in the stress direction, resulting in improving the binding properties has the greatest effect on the Z-direction strengths of the pulp. Mechanical pulps ability to bind is greatly affected by the amount of fines in the pulp. In this case, the peel strength depends mainly on the amount, quality, retention and distribution of the fines in the sheet. (Levlin 1999, 138)

5.3 Other properties

5.3.1 Bulk

The final pulp mass density is usually referred by bulk. Bulk is obtained as a measure of density by dividing the weighed basis weight with the thickness of the pulp sheets. In general for cardboard and paper the desired properties are high bulk combined with low density, taking account that all the other critical properties have been achieved. (Häggblom-Ahnger. & Komulainen 2006, 83)

$$\text{Bulk} = \frac{1}{density\left(\frac{cm3}{g}\right)} = \frac{grammage\ (\frac{g}{m2})}{thickness\ (\mu\text{m})} \qquad (15)$$

The basis weight is the weight in grams of one square meter of sheet made from the pulp. The thickness is the distance between the surfaces of several individually measured sheets as their average. The importance of bulk to BCTMP comes from the rigidity required for the board. With three-layer boards high rigidity is sought so that the middle layer of the board is made as thick and bulky. These features also allow you to make thin, however firm products that feel sturdy without lifting the basis weight. Bulk also correlates with opacity and stiffness that is very important in packaging products. (Lumiainen 2000, 91)

However, lifting a bulk does not often support the emergence of other quality characteristics of the pulp. To obtain high bulk, it would be good to have large number of long fibers and very few sticks in the pulp. The amount of long fibers can be influenced by keeping the CSF level as high as possible. Long fibers can cause problems with a paper or board machine so therefore the best stiffness properties are obtained from high density hardwood, such as birch, or by putting long fibers of coniferous wood into LC refining in addition to mainline refining. In the board manufacturing process bulk is mostly affected by calandering and wet-pressing, but also refining has the effect of increased refining leading to decreasing bulk. (Häggblom-Ahnger. & Komulainen 2006, 84)

5.3.2 Freeness

CSF values of pulp are often used in the comparison of mechanical pulps, as the most important characteristics are strongly correlated with the CSF level. CSF represents the degree of refinement of the pulp, i.e. the further the pulp is refined, the higher the fiber content specific surface area is and the lower the CSF value is. In higher freeness levels, longer and stiffer fiber structures can be obtained. The CSF-value is used in the determination of the dewatering capacity of the mechanical pulp and it is affected heavily by the fines content and compressibility of the pulp. (Hiltunen 1999, 39)

Water pH, conductivity and hardness affect the CSF-value due to swelling of the fibers and fines. Therefore, the CSF- value should be performed in a standardized manner with ionized or distilled water, to avoid problems with the water quality. When preparing BCTMP, a CSF level of ≥ 400 mL is aimed at the board. Lower freeness needs more refining, so it is more costly to produce than higher freeness. (Lindholm et al., 2009, 275.) At a higher level of CSF, long and rigid fibers are obtained in BCTMP that give the final board product has a high volume, lower basis weight and a rigid, bulk structure. However, the higher the CSF level in the pulp is, the lower tensile strength of the pulp is. (Heikkurinen 2009, 457)

5.3.3 Stick count

Stick content is used to describe the fineness of the pulp as ticks are coarse bundles of fibers and pieces of wood that have a negative impact on the process. These bundles and wood pieces can be seen without a microscope, they are 1-4mm in length, but 0,1mm thick. Sticks are crated in refining when fibers change shape and surfaces break. They cause cracking when accessing the paper / cardboard sheet and their number can be affected by latency removal. Straightening the curls prevents the formation of sticks and facilitates sorting, where the sticks can be separated from the pulp. (Kappel 1999, 43)

The number of sticks is usually calculated as a percentage of the weight of the pulp. Ideally, all the sticks would go directly to the reject where they would come back as an accepted fraction back to the process. This is not possible in practice and there are always some sticks left in the pulp accept. Several devices have been developed to monitor the number of sticks, as plate, screens and annular slits are used. (Heikkurinen 2009, 458)

5.3.4 Fiber length

Fiber length greatly affects the strength properties of the pulp. Longer fibers are capable to form significantly more fiber-to-fiber bonds with each other compared to shorter fibers. They also bind more strongly to the formed fiber network. During defibering, wood chips open into individual fibers and fines. Fiber shortening occurs mostly during refining between the refiner blades. Fibers also break in refining and their structure changes. In long fibers, the curling is the dominating factor in tensile strength. (Lucander 1988, 6)

It is possible to reduce fiber breaking with chemicals and heating the pulp in the same time achieving better strengths for the pulp. BCTMP has also coarser fiber due to the lignin in wood content, which makes the pulp a high-yield product. (Heikkurinen 2009, 458). Fiber length can be measured relatively easily, and fiber length and fiber length distribution are the most important dimensions and they can be measured for example with a Kajaani FS-200 sampler measurement continuously on-line from the process as seen in table 6. Other measurable properties are fiber width, form factor, curl, longitudinal pulp and of fines amount. Measurements can be made on-line during pulp production and in the laboratory afterwards from pulp samples. (Eskelinen 1999, 97)

TABLE 6. Nordic pulp and CTMP fiber dimensions from soft pulp with Kajaani FS-200 (Eskelinen 1999, 96)

Pulp	**Species**	**F. length avg.**	**F. coarseness**	**F./1g of pulp**
Chemical	Pine, Spruce	2,1 - 2,2 mm	0,20 – 0,23 mg/m	6 x 10^6
CTMP	Spruce	2,2 – 2,3 mm	0,38 – 0,42 mg/m	3 x 10^6

5.3.5 pH and conductivity

With pH-measurement it is possible to detect the presence of acidic and alkaline ions in the pulp. Optimal conditions include low concentration of transition metals. During pulp preparation, the pH depends on various factors, such as wood species, reaction temperatures, reaction times, chemicals used or pulp consistency. By constantly monitoring and adjusting the pH, it is possible to influence the final product properties, especially strengths, bulk and opacity. (Hausalo & Söderhjelm 1999, 112)

The conductivity of BCTMP has big effect to the results of pulp permeability tests. Even the smallest changes in dissolved salts and pH may affect the permeability of the pulp. Conductivity measures the amount of these dissolved salts, or electrolytes, in water and tells the level of residual ionic impurities in the pulp. (Hausalo & Söderhjelm 1999, 113) The conductivity of pulp describes its ability to conduct an electric current and it depends of concentration, temperature, ion mobility and charge. Rising temperature leads to more mobile ions leading to increased conductivity. For measurements to be comparable with each other, they must be reported in reference temperature. (Jemway n.d.)

5.3.6 Odor and taste

Folding cartons made of BCTMP are often used in food packaging as packaging material, in which case no transfer of odor of taste can take place to the packaging material. The packaging material must also be microbiologically clean. Potential odor and taste nuisances are tested by organoleptic tests, where the Robinson test is one of the commonly used methods. Cellulose, hemicelluloses and lignin contain small amounts of extractants that can cause problems with odor and taste problems in the final product. (Hausalo & Söderhjelm 1999, 111) Testing is done separately a selected test group that uses reference samples to determine the suitability of the pulp for food use. Chocolate, which is very sensitive, is often used as the product to be tested from the packaging material for a contagious odor or taste. (Kiviranta 2000, 56)

6 INFORMATION LEADERSHIP FOR CHANGE MANAGEMENT

The mill knows the important parameters for pulp and the mill director and the middle management also know what must be changed technically to achieve the new production quality goals. But how to communicate these changes to the operators and supervisors in an environment, that values stability and minimal tampering with the product. Good thing is that mills are more adjusted to adapt towards changing because the markets move faster and faster every year and businesses must implement new processes and integrate new technologies in order to adapt efficiently for the ongoing change. In this chapter the methods in change management were introduced, it is a systematic approach for businesses to implement and adapt towards changes in their business and incorporates innovative strategies and effective variables in a efficient way. (Murthy 2007, 22)

In pulp and paper mills it is possible that change is viewed as threat because if the need for change is forced to the operators from the top level it is possible, that it is not perceived as positive. Especially in this kind of situation where the mill operators are working within their best knowledge, it might be hard to start justifying new ways to operate if there is no major issues in the daily operations. Change also affects the whole organization from leadership to the operator and communicating to the operators that how the organization reacts to change is a crucial element when implementing new technologies and processes. People make the change happen at the workplace and therefore it is the mill’s responsibility to guide the people through the change. In meanwhile the workplace created is supportive, transparent and more change oriented. (Roswell, Stavros & Sullivan 2016, 41).

In the ideal situation the operators understand instantly why new methods of operating the process is needed to cut the costs. But since there are five different shifts that already have different kind of operating models for the process it is unlikely that all the shifts will instantly form a unified stance of how to change their individual operating models. As much as the leaders of the mill would want to make the change happen right away, change really occurs at the bottom. The management must work in line with the supervisors whose duties are narrowed down to advising the management on this adjustable area and in the implementation of new process model. The supervisors are the ones leadership trusts to deliver the mill's new vision to the mill floor level and they must have not only the full support of the leaders, but the time and space to deliver it. (Gesme & Wiseman 2010, 258)

This change management in the optimal stage should be always on, because also the customer needs and therefore the products are changing always. Change should not be perceived as a transition from on stable environment to another, but instead it is a constant evolution and organizational agility by learning being the only focus. (Perlman & Leppert 2013, 60.)

The most difficult situation for a change management process would be in a mill, that has been through many unsuccessful change management processes. In that kind of environment, the trust from the operators to the management is damaged and the current way to operate is strong. If this process would be implemented into a that kind of hostile environment, what would be the steps of implementation remembering in the same time, that change management is a set of plans, actions, processes and decisions where change is executed on a sustainable basis. (Bevan 2011, 217)

6.1 Key dimensions

As stabile and constant a mill environment is due to huge hardware investment costs in the industry. In a mill environment the change can be further separated into four cycles of change including the levels and contents, processes and means, stages and episodes and for last, the patterns and sequences. Mintzberg and Westley (1992, 41)

Change exists on all levels of the organization, this means that it will affect the most conceptual levels to the most detailed, concrete levels of the operations of the organization. This concept is illustrated by changing mindset or culture compared to machinery or staff. The table 7 shows that to further specify the terms according to change in organization and change in strategy resulting in structure where structure is conceptual and systems are concrete when mentioned organizationally but in the same time positions as conceptual and programs as concrete represent change in strategy. (Mintzberg & Westley 1992, 41)

Table 7: Contents of organizational change (Mintzberg & Westley 1992, 40)

	Change in organisation (state)	**Change in strategy (direction)**
More conceptual (thought)	Culture	Vision
More conceptual (thought)	Structure	Positions
More concrete (action)	Systems	Programs
More concrete (action)	People	Facilities

In this case it is possible to plan the change, the change will not be sudden, and it is possible to implement a change process to deliver the change. Mill management must take account the whole organizational behavior including the possible development and struggle stages. Considering the major drivers for change in this case being more economic than social, there is also a social aspect in here when thinking about the next change management project after this. If the mill management succeeds in this economically based change management project, the probability for the success of the next project also rises. It can be more social like broadening the employee base education scope from only technical and business fields to others. Kotter (2012) says, that by identifying triggers such as technology, business markets, social values and demographics it consequently reveals that there are not only economic factors forcing the change in organization, but the social aspects will lead the change.

Since the mill ultimately needs a proactive change model and it must also identify success factors and pitfalls from the change process. It is therefore possible to take into account plans and visions instead of erratic and spontaneous experimenting of “what works or can this work?” In eyes of the stakeholders, all the strategies, culture and leadership are second to the objective of how the process changes and how will it be changed. (Alvesson & Sveningsson 2016, 18-19)

6.2 Pre-change

The first steps of change management is to unfreeze the status quo meaning that to obtain the needed involvement from the stakeholders a sense of urgency must be created. Sense of urgency in this case does not mean a vast task list but as a passion of finding the real solution and learning while finding it. (Kotter 2008, 6) In this case the need has been presented as more stable process operation and less process variation and the operators know that it is attainable since they have partially been able to operate the process with the needed accuracy already before for extended periods of time, but not constantly.

Team building would be the next step, since there is no way a single person can implement this kind of major organizational change alone. Trust between team members is also an important factor of success, the team must have a common vision and strategy if they want to break the employees change resistance. The subjects of change must have a appealing picture of the future and they must understand how the vision can be achieved logically and why the vision must be fulfilled? (Kotter 2012, 73)

In a pulp mill environment this team would consist of a work group involving one participant from every shift, preferably an operator. One participant from the shift engineers and one or two participants from the management. When bringing the team together they must be informed about the purpose, knowledge, time commitment, process definition and clear role allocation. It is also important that the ideas and expectations of team members are committed, so that it is possible to can see after the project what went according the plant and what can be improved on. The team must discuss the vision with each other and a good way to do that is to describe and compare the methods they are thinking to formulate the change. Eventually the team must form a clear agreement regarding the required steps so that the pre-phase can be concluded. This also means that the balance needs to be unfrozen before old behavior can be abandoned and new behavior adopted. (Burnes 2004, 985)

6.3 Making the change

To move into the implementation phase, the current frozen situation must be understood, and the further steps of the process must be understood. The first step would be to make people feel empowered by the change and creating and alignment with the new structure and the people. Without suitable skills, people feel disempowered. (Kotter 2012, 119) Team would have to arrange process trainings for the operators and to be inclusive, offer it to every employee on the mill, this would also build momentum meaning that the inclusiveness turn neutrals into supporters and reluctant supporters into active ones. There should always be a dedicated person in the mill to ask questions about, to have the support for the night shifts and weekends for potential hick-ups in the process. The transparency must be in the center, everyone must be informed and support even by intervening must be in place. (Jabri 2012, 20)

In reality this would mean an extra-person to the shift dedicated to monitor the movement of the refining energy consumption and chemical consumption and then explaining to the rest of the shift what is affecting the consumption rates at this moment and what the shift can do to keep it steady or reduce it. When the shifts understand in detail what is happening in the process, they want to start implementing it into their own way of operations. If this method feels to excessive with multiple additional operators, the method can also be piloted first in one shift and gather knowledge of the results it had considering the change process.

6.4 Upkeep

Change management does not end when the shifts have started to operate in the new way, there is still a long way until the change is consolidated into the corporate culture. The support must stay in the place to spread the information and security to the new model and all stakeholders must stay involved from the top management to the operator level. The change can be expanded and anchored with successful change management projects and steady leadership.

This will help the future change projects to gain momentum, or in the best case take the momentum of this successful change project. Luecke (2003, 45)

The dilemma between keeping the change ongoing and risking the organizational change fatigue or that the achieved status starts to change into something different and between Burnes (2004, 981) steps of refreezing and stabilizing the organization for new balance for avoiding behavioral regression is difficult. Successful change is also hard to make and refreezing makes the next change a bit harder, however if the corporation has change management experts that know the process and are well educated in unfreezing and refreezing, it is possible to get the best of both worlds. Kotter (2012, 131) says that it is also possible to bring new people in after the change, so they will only know the new way of doing things.

6.5 Summary of the literature for BCTMP-production

For a mill to be able to produce market pulp the quality starts from the wood usage. Not only regarding the fiber length differences between softwood and hardwood, but also the amount of chemical compositions, extractives and inorganic compounds. According the literature part, it would not only suggest running different kind of refiners for softwood and hardwood, but also to stack the separate wood species into their own silos. Each wood species have their unique characteristics and they can be optimized accordingly. Of course the long fiber softwood usage should be minimized in effort to minimize the costs but also for example mills residing in the southern hemisphere should also take account the differences between the individual properties of acacia and eucalyptus and optimize their refining and chemical pulping lines accordingly. At the moment it is not common to have different lines for different species inside for example deciduous trees.

There are also a lot of different options to choose from regarding the initial pulping method. The most used one and in the same time most straightforward method would be to only use mechanical refining to refine the woodchips into the desired freeness level. However it is possible to impregnate the wood chip before refining to soften it up and to reduce the amount of energy needed to obtain the desired freeness level, this is called chemi-thermomechanical pulping and it also helps with the bulk and fiber length of the end product. Then when peroxide bleaching is added to the refining process the mill has in the current BCTMP-process.

Regarding the process there were also chapters about the refiner structure and refining consistency, that help to lower the cost of refining and to keep the mill up and running without heavy maintenance costs. Also different materials used in refiner segments were wrought and what are the benefits between the classic single disk refiner versus the newest twin flow refiners.

Regarding the optimal bleaching result and what is affecting the pulp before actually dosing the bleaching chemicals, there are chapters about the reject handling, cleaning and sorting of the pulp. The fibers must be as intact and long as possible after the refining and the behavior of extracts should be as well known as possible before the bleaching stage. The refining stage is also very delicate for any seasonal variance of the woodchips regarding for example in the Nordic countries the chip quality between winter and summer. Also, the wear and tear of the refiner segments must be taken into consideration when discussing about the optimal process parameters.

The mills also have ongoing modernization projects for the process where they are reviewing the possibilities to transfer from high consistency refining to low consistency refining. This improves the printability properties and makes the fibers form stronger internal bonds leading to better strength properties for the pulp. When a mill is starting a project to model the process there is always the possibility that the project will end up suggesting new hardware investments and after that the modelling work must be started from scratch with the data from the new process equipment.

Bleaching part of the literary review highlights the various chemicals commonly used in the bleaching process. Focusing on the peroxide usage since it is the bleaching chemical used alongside the pH-control chemical caustic. The reactions of bleaching are explained as well as the process parameters affecting the bleaching result alongside the dosage, which are consistency, pH/alkali – relation, temperature and exposure time. Also the possibility of multiple-stage bleaching is wrought as it the most advanced bleaching technology used in the BCTMP-mills. Multiple-stage bleaching also brings a lot more optimizing potential and modelling potential, because as the bleaching curve between the end brightness and chemical dose is not linear, it is possible to optimize the bleaching curves as well. With the current data originating from a mill that bleaches only in one stage the amount of optimization is smaller. When knowing the brightness of incoming pulp, outcoming pulp and the chemical dosages it is possible to model the effect of the chemical very precisely. When adding additional bleaching stages to the process, it is possible to balance the different stages to optimize the bleaching chemical amount.

In the end of the literature part the desired end-quality properties for the pulp were researched and why they matter for the customer. Optical properties are of course the most obvious to the naked eye and that is why also the experimental part focused on the chemical savings of the bleaching chemicals. It is also important to remember that the BCTMP-pulp can be used to increase strength properties not only in a printing and writing paper, but also in the top layer of cardboards. Depending on the printing method the desired optical properties differ vastly.

As mentioned below, most customers value the strength properties of the end product above all. This is because when adding relatively cheap mechanical fiber to the pulp mix it is possible to reduce the amount of higher cost chemical pulp from the mix. Basically, it is possible to get the same strength properties for the end product with a smaller grammage leading to huge savings in kraft-pulp consumption. Other important properties addressed are the fiber properties and freeness, as the more refined the pulp is the better strength properties it has. The curve between refining and for example tensile strength is also not linear, so it is important to achieve a optimal refining level for the maximum benefit between strength and refining energy usage.

It is unclear for what end product the pulp is used in the mill this thesis data was acquired from. Of course, it is probable that the mill produces market pulp, but in the future it might be possible for a BCTMP-mill to concentrate solely to one kind of BCTMP suitable for example only white-top FBB-line properties. This would mean that the mill would optimize it’s freeness and brightness properties only for this one grade of cardboard instead of producing market pulp for many different kind of products.

Despite the BCTMP-processes varying from mill to mill, refining and bleaching parts of the mill are both integral parts of every BCTMP-process. Therefore it is natural to start looking for savings in the process from these departments as have now been done with the data analysis.

In the last chapter the possible change management methods of implementing new operational model into a mill environment were studied. What kind of change is possible, how to prepare for the change and how implement it. There are many different change management theories, but eventually they all say that the whole organization must be involved and the change must be transparent. Also the emphasis after the change has been implemented must be on the upkeep, since after the organizational change the cultural change takes up to 1000 days.

7 EXPERIMENTAL PART

7.1 Methodology

The process industry has ever-growing interest to make the processes more efficient. Now this subject has been entered with the opportunity to model the quality values of BCTMP-pulp to Optimize the pulp quality for the customers. From all the different qualities of the pulp the most important ones for the customers are freeness because it has a high correlation with strength properties and brightness, because it has high correlation with printing properties.

Controlling the quality in a pulp mill from chipping to baling has always been challenging without adequate information about the properties of the fiber and because the fiber is changing during and in between different process phases. In a pulp mill the final quality targets are always predetermined based on what fixed grade the mill is running.

Pulp quality variables are often hard to measure online and that is why the key strength properties of the pulp is needed. Freeness correlating with strength properties in a pulp mill is a given. However, when the pulp arrives at a paper machine only modelling freeness for paper strength properties is not adequate anymore and the mill has to use fibrillation as a model input together with freeness and fiber properties.

The stabilization of pulp quality is hard, pulp mills usually combine multiple lines of pulp flow and the blended pulp is then dried, baled and shipped to the customer. Also the large variability of the pulp quality regarding brightness and freeness causes problems to the end user. Controlling and stabilizing the refining and chemical dosing not only brings savings to the mill in reduced chemical and energy usage, but also makes the end product and the entire process more stable as a whole. If the paper or board producer can trust the product with great certainty, they can run their process more optimally meaning reducing the amount of other fibers in the mix leading to reduced grammage, more even water removal and therefore reduced steam consumption.

When modelling the key quality variables of pulp as freeness and brightness, it’s also important to know how they affect the end properties. Freeness affects the tensile strength but also bulk and as they tend to correlate inversely, it is hard to get high strength end product with good bulk properties. In the BCTMP mill the freeness-index was modelled and the inputs for the model are Valmet MAP Q analyzers freeness and the specific energy from the mill DCS-system. This freeness model is used to calculate potential savings in the operations of the BCTMP-mill. Also final pulp brightness was modelled and there the inputs were the start brightness and the chemical usage.

This methodology only needs the data from the mill DCS-system to be transferred into an excel-file. From these very basic tools it is possible to find the correlation and causality affecting the key pulp properties. These methods can also be implemented to other parts of the mill such as kraft mill fiber line, recovery boiler, stock preparation and paper machine. If the mill can acquire the data from the measurements and analyzers, it can optimize the process. When it is possible to not make overquality with pulp, also the variability of the process decreases. This improves the uniformity of the process, but it does not necessarily make the economics better. The mill needs to have dedicated operators to push the process towards more economical direction.

For the data, two weeks of data was obtained from the mill. The mill engineer downloaded the data from the mill DCS-system into an excel-file. Data was in the right shape and no interpolation is needed, some empty data points had to be filtered out. Analytic phase is usually divided into two categories, the initial pulp mill raw data analysis phase and the main benefit and process analysis phase. The main benefit and process analysis methods is used to generate end results providing new information gained from data. For the raw data analysis for the pulp mill linear regression is used, which is a mathematical way of sorting out which of the variables in a data package have an impact and which have the biggest impact.

After the used methods have been decided, the data mining starts. This is the part where hidden information is searched from the data with the linear regression analysis. This requires not only understanding of the data analysis process, but also the pulp making process. The purpose of the linear regression analysis is to check the coefficients of each of the variables, in this case for example SEC and freeness and declare the relationship between variables more specifically.

The results from the linear regression provided new information on what variable could cause other variables to change directly. The main purpose of the analysis was to detect how selected data of the pulp mill affected selected variables. Data analysis of the data provided knowledge that the selected variable do cause straight effect to other dedicated data variables.

What comes to the mill data, pulp production remained rather stable over the hours 1-100, The hours after that showed some fluctuation but overall the pulp production rate was kept in the target level for tens of hours at a time. Figure 7 illustrates the pulp production of the BCTMP – line during the data period.

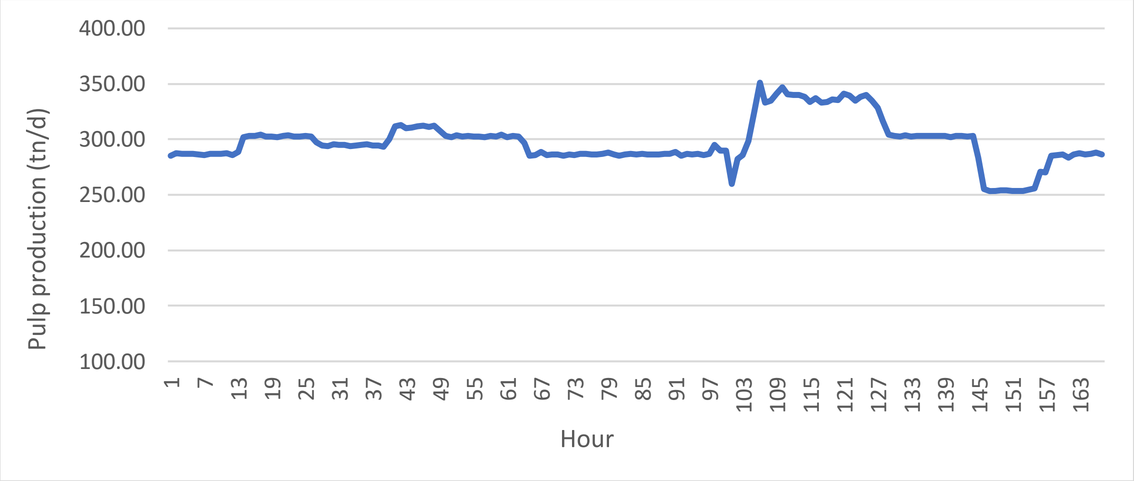


FIGURE 7. Pulp production per hour

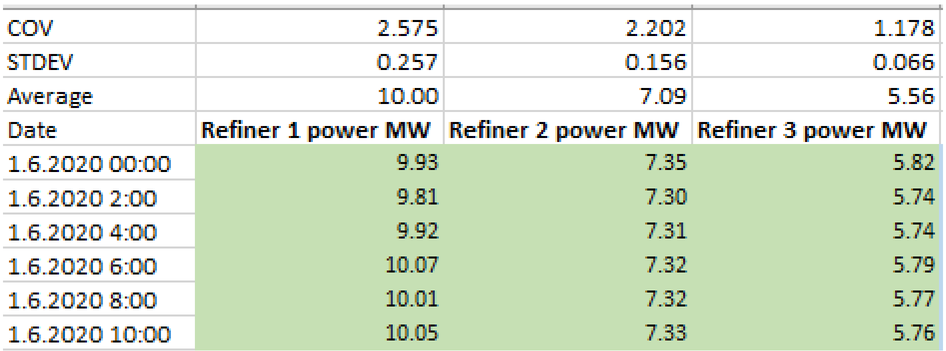
7.2 Energy consumption

To calculate the potential energy savings the first thing needed is the information about how much energy the process is consuming, how much pulp is going through the process and how the pulp is affected by the refining stage. Also it is required to know the mill targets for the pulp CSF.

7.2.1 Calculating the SEC

Specific energy consumption means the amount of energy the refining line is using to refine the pulp going through the refiner. The first important data point is how much power the refiner is using and that can be seen in table 8 where on the “Average” – row the average energy consumption of the refiners can be seen from the two week period.

TABLE 8. Mainline refiners power consumption

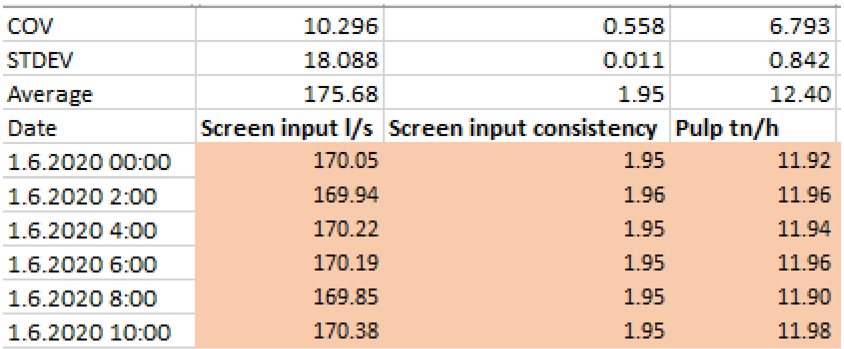


COV	2.575	2.202	1.178
STDEV	0.257	0.156	0.066
Average	10.00	7.09	5.56
Date	**Refiner 1 power MW**	**Refiner 2 power MW**	**Refiner 3 power MW**
1.6.2020 00:00	9.93	7.35	5.82
1.6.2020 2:00	9.81	7.30	5.74
1.6.2020 4:00	9.92	7.31	5.74
1.6.2020 6:00	10.07	7.32	5.79
1.6.2020 8:00	10.01	7.32	5.77
1.6.2020 10:00	10.05	7.33	5.76

Adding the average energy consumptions of the refiners together it is possible to calculate that on average the refiners have the power of 22,65 MW. To be able to know how much energy refiners are delivering into the fibers it is crucial to know how much fiber is going through the refining line.

This calculation can be made from the values of table 9 when from the data the amount of the input of water and fibers to the refiners is known and also the fiber consistency of the input. From there it is possible to calculate the amount of pulp going through the refiners and in this case it totals for 12,4 tn/h.

TABLE 9. Pulp tonnage going through the refining line



COV	10.296	0.558	6.793
STDEV	18.088	0.011	0.842
Average	175.68	1.95	12.40
Date	**Screen input l/s**	**Screen input consistency**	**Pulp tn/h**
1.6.2020 00:00	170.05	1.95	11.92
1.6.2020 2:00	169.94	1.96	11.96
1.6.2020 4:00	170.22	1.95	11.94
1.6.2020 6:00	170.19	1.95	11.96
1.6.2020 8:00	169.85	1.95	11.90
1.6.2020 10:00	170.38	1.95	11.98

After the amount of pulp and refining energy is known, the amount of energy used must be divided by the amount of pulp going through the process every hour and get the amount of energy used for every pulp ton. Figure 8 illustrates the total specific energy consumption in the mainline refiners.

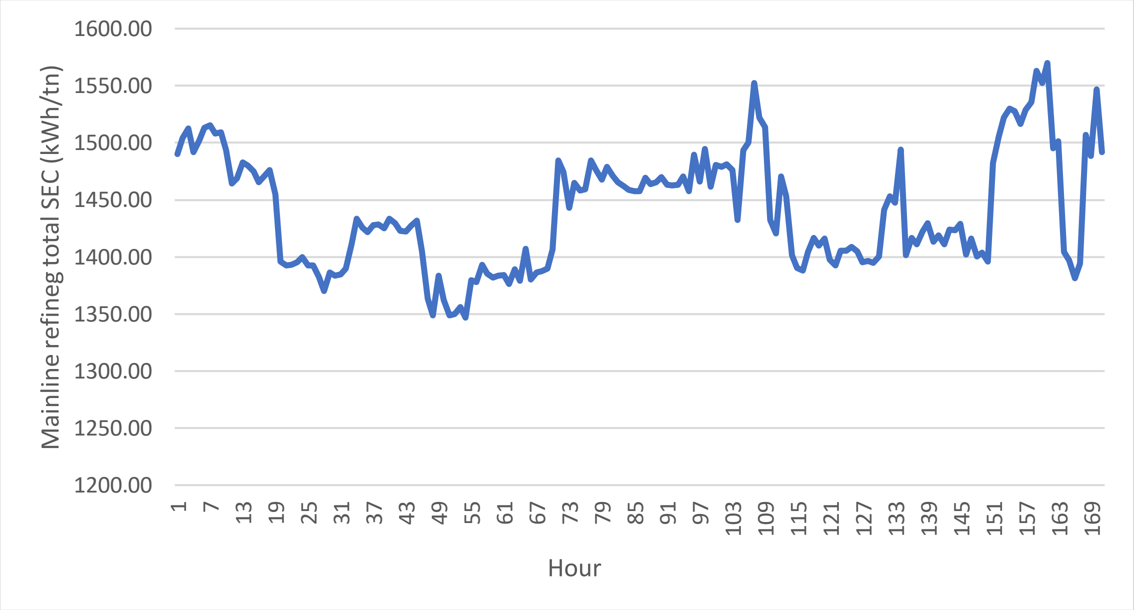


FIGURE 8. Mainline refiners total SEC

From these it is possible to calculate the amount of pulp in the process where the input from the screen as litres per second is first transferred into pulp input without the water by multiplying it with consistency of the diluted pulp. After that it is possible to transfer the seconds into hours by multiplying the number by the amount of seconds in one hour which is 3600:

$$\text{Screen input l/s} * \text{consistency} * 3600 = \text{pulp ton/h} \qquad (16)$$

Every refiner has a tag in the process. Tag meaning the identity number the mill DCS – system has been given to recognize what refiner is in question and what are the parameters the refiner is currently operating on. For example the mill DCS – system gets the energy consumption information from the refiner and the energy consumption can be controlled by the operators.

This particular process has three refiners in the same refining line, meaning that to get the specific energy consumption for every pulp ton refined, every refiners energy consumption must be added together and then divide it by the amount of pulp going through the refiner line.

Below is the formula for the refining line energy consumption. R1, R2 & R3 are the refiners and to calculate the SEC for the energy consumption for each refiner has to be known. After that it is possible to add those numbers together and divide it with the amount of pulp that has gone through the process. Now it is possible to know how much energy is used to refine one ton of pulp.

$$R1\ (kWh) + R2(kWh) + R3(kWh)\ /\ \text{pulp ton/h} = \text{Refining line SEC kWh/ton} \tag{17}$$

The average refining SEC is about 1440 kWh/tn.

The average SEC for the pulp line is resolved and the next resolved variable is how much the refining affects the freeness and fiber length in the process.

7.2.2 Affecting the fiber

Checking the fiber tags for the CSF and fiber length – values before and after the refining is vital. In this case the measuring points are after impregnation and before the disc filter.

In this stage it is possible to notice, that the average incoming pulp to refining has the CSF of 203 mL and after the refiners it has the CSF of 96 mL. The mills target for CSF is 105 mL so it is easy to realize that they are producing overquality. They could be refining a lot less and using less energy to reach the CSF average target of 105 mL. To achieve this the mill should be able to also decrease the variation in the process. Coefficient of variation gives the information of how far the random variable is typically from the expected value

At the moment the coefficient of variation of the freeness in the process before the disc filter is 4,62 mL meaning that if the process must be at all times below the target of 105 mL, the freeness target should be 100 mL. This would greatly reduce the savings potential and the mill should focus of reducing the variation of the process to be able to gain the benefits from the higher freeness – target. Figure 9 illustrates the freeness development in the process before the disc filter.

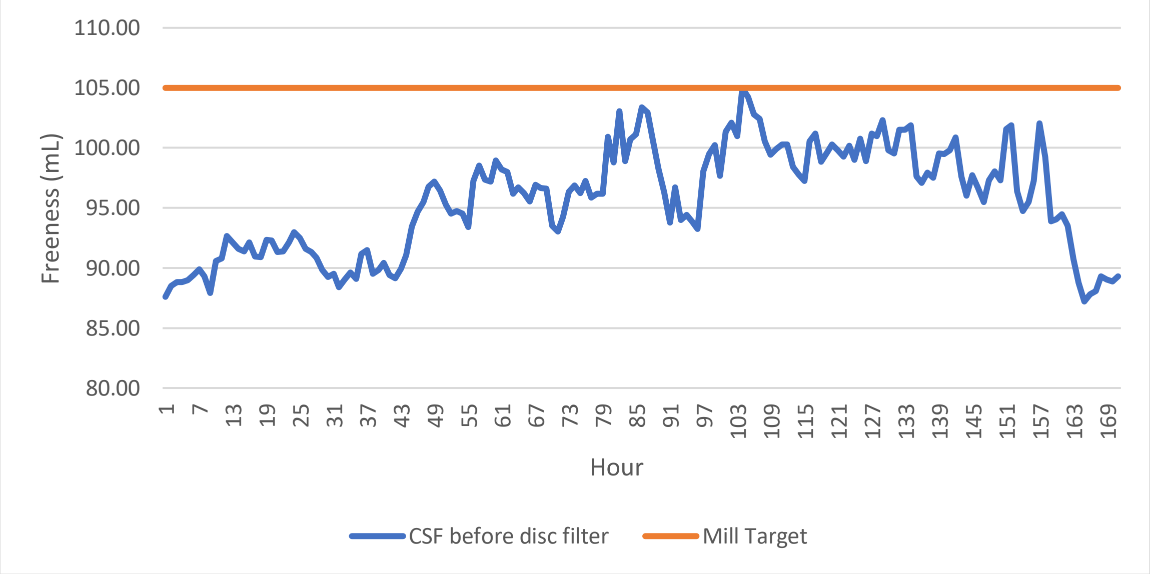


FIGURE 9. Canadian Standard Freeness before disc filter

For fiber length the mill does not want to go under 1,25 mm but as the average is 1,35 mm in the disc filter and with these process changes increase the fiber length as the fiber is not refined as much, fiber length does not bring restrictions to the CSF energy saving. Figure 10 illustrates the fiber length in the process before the disc filter.

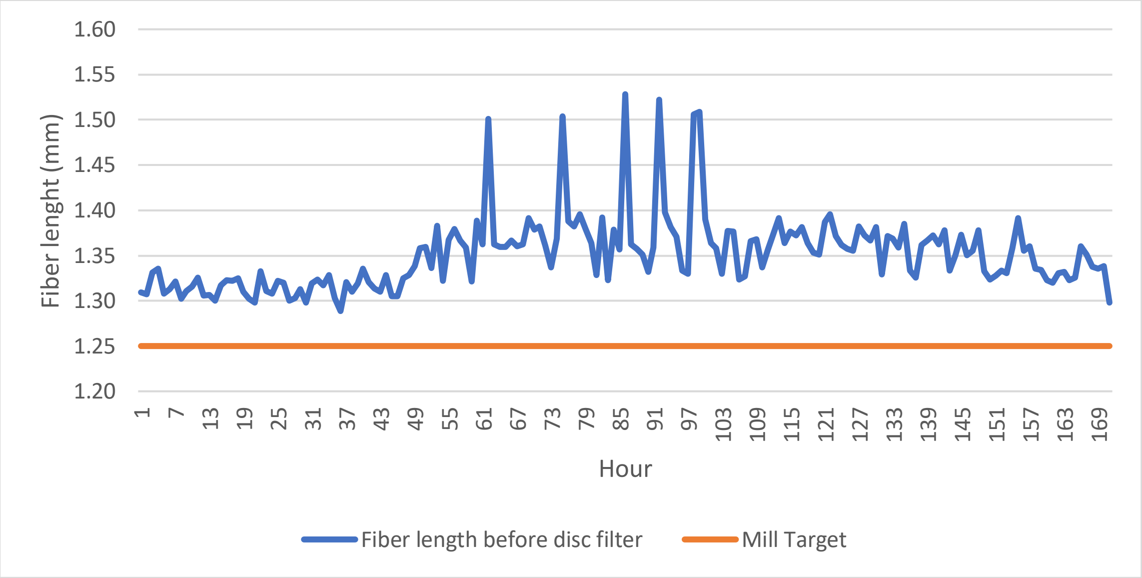


FIGURE 10. Fiber length before disc filter

7.2.3 Modelling and calculating the potential savings

As it is possible to focus only on the CSF-value of the process, modelling the effect of SEC to CSF is the next step. It is possible to utilize the Multiple linear regression analysis – tool in Excel and check how big of an effect one value of SEC has to CSF. Linear regression is a way to model a relationship between sets of variables, in this case SEC and CSF. The result is linear regression equation that can be used to make predictions about the data.

According to Alan O. Sykes (Sykes 1992, 5) simple linear regression can be expressed as follows:

$$I = a + \beta E \tag{18}$$

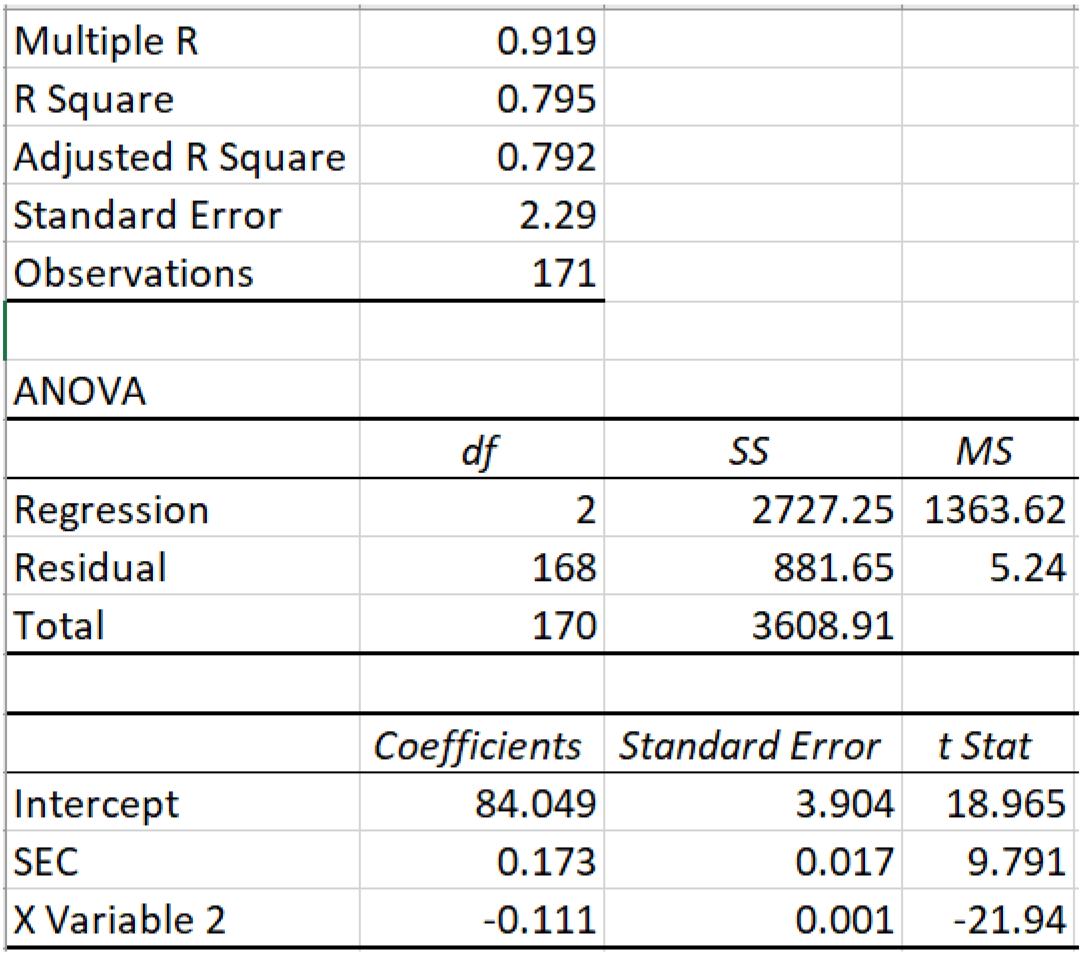
Where the I is dependent variable, E is independent variable, a is constant term and β is coefficient of the variable E.

For excel regression analysis output the statistic are Multiple R meaning the correlation coefficient telling how strong the linear relationship is when value of 1 means a perfect positive relationship and value of zero means no relationship at all. R squared means the coefficient of determination telling how many points fall on the regression line, for example 70% means that 70% of the variation of y-values around the mean are explained by the x-values. This can also be explained as 70% of values fit the model. (Salkind 2015, 122)

Intercept is the expected mean value of Y when X = 0.

Studying the regression analysis done on the mill data in table 10 shows us, that the coefficient of SEC is approximately 0,17 meaning that every time the CSF value goes one value lower it is because the SEC – value has gone six values higher. So ultimately one CSF point drop in freeness requires the amount of refining energy to increase 6 kwh for a pulp ton.

TABLE 10. CSF modelling with SEC



Multiple R	0.919		
R Square	0.795		
Adjusted R Square	0.792		
Standard Error	2.29		
Observations	171		
ANOVA			
	df	*SS*	*MS*
Regression	2	2727.25	1363.62
Residual	168	881.65	5.24
Total	170	3608.91	
	Coefficients	*Standard Error*	*t Stat*
Intercept	84.049	3.904	18.965
SEC	0.173	0.017	9.791
X Variable 2	-0.111	0.001	-21.94

This means that if the process target would constantly be CSF 105 mL instead of their current running rate of 96 mL, they would use 6*9 = 54kWh/adt less for the end quality product. As the difference between the average CSF in the process was 9 mL. (105 mL – 96 mL). This would mean that as the original refining energy consumption was 1440 kWh, the drop compared to the original would be:

$$\frac{54\ kWh}{1440\ kWh} = 0{,}038 \tag{19}$$

Meaning a total of 3,8 % reduction of energy consumption. The SEC relation to CSF can be seen in table 11.

TABLE 11. Modelling the effect of SEC to CSF

Multiple R	R Square	Intercept (Final CSF)	X Variable 1 (SEC)	X Variable 2 (Latency 1 CSF)
0.919	0.795	84.049	0.173	-0.111

7.3 Chemical consumption

As this process is one-stage bleaching, to model and calculate the potential savings in the bleaching process several data points are needed. Start brightness, the amount of pulp going through the process, the amount of peroxide and the final brightness. In some mills it is possible to also optimize the use of NaOH, but in this process the mill has not dispensed it in relation to H2O2, so the amount of NaOH is not relevant. Assumption based on theory is that when the amount of H2O2 reduces also the need for NaOH reduces. Figure 11 illustrates the brightness difference between the fibers before and after the peroxide bleaching.

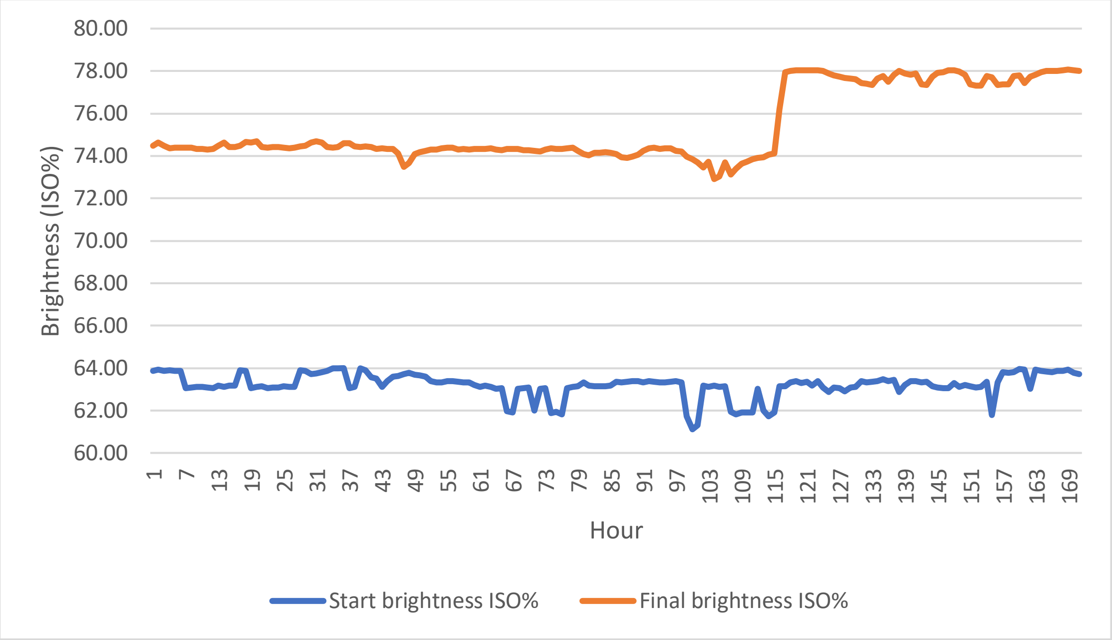


FIGURE 11. Brightness comparison before and after bleaching

When calculating the savings potential for the bleaching it should be noted that the gain is not linear and for that it is possible to calculate the different H2O2 gain to brightness from two different levels of bleaching targets. In this process the mill has two different grades of brightness and it is also possible to calculate the average peroxide dose for both grades where it is possible to get the slope and the coefficients for the brightness gain. Figure 12 illustrates the peroxide dosages effect to the final brightness

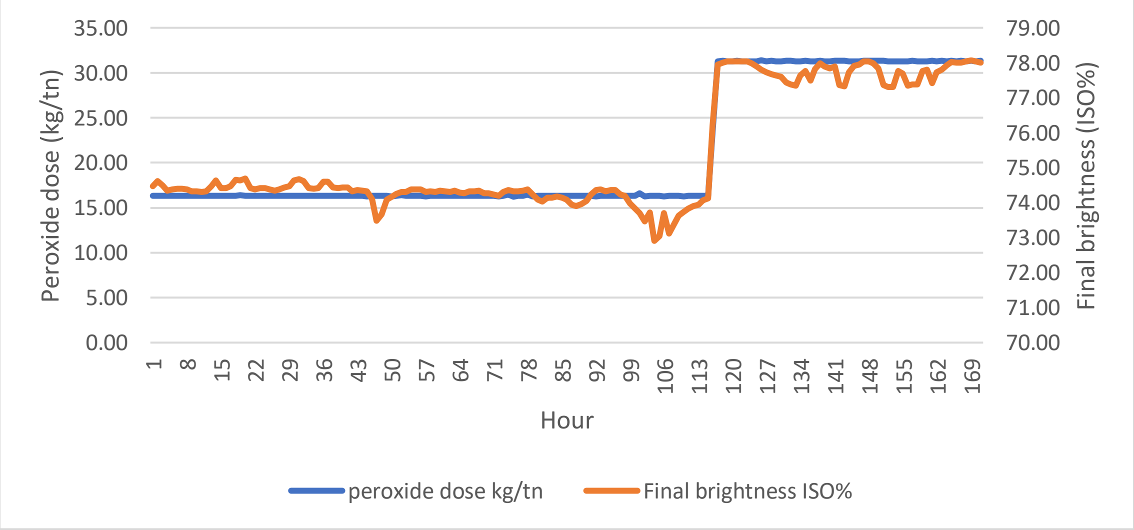
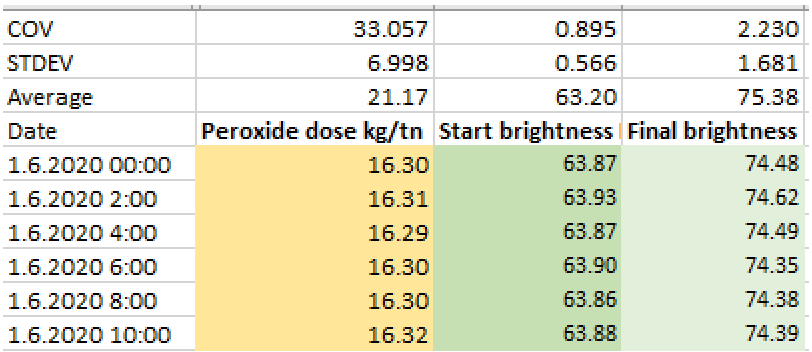


FIGURE 12. Peroxide dosage and final brightness

The mill had two brightness targets, ISO % 73,0 and ISO % 77,0. It is common knowledge that the more bleaching chemical used, the less effect you have. First the mill process gain of their lower brightness target was modelled and it resulted in the average of 16,3 kg peroxide for one ton of pulp:

The first stage of the modelling is to check from the data how much peroxide is dosed into the process, what is the start brightness and how much it increases with the current dosage as illustrated in table 12.



COV	33.057	0.895	2.230
STDEV	6.998	0.566	1.681
Average	21.17	63.20	75.38
Date	**Peroxide dose kg/tn**	**Start brightness**	**Final brightness**
1.6.2020 00:00	16.30	63.87	74.48
1.6.2020 2:00	16.31	63.93	74.62
1.6.2020 4:00	16.29	63.87	74.49
1.6.2020 6:00	16.30	63.90	74.35
1.6.2020 8:00	16.30	63.86	74.38
1.6.2020 10:00	16.32	63.88	74.39

TABLE 12. Brightness variables

So for the process average for the whole two week data patch the dose is 21,17 kg/tn but for only the low peroxide dosing it was 16,3 kg/tn. Then it is easy to make a linear regression and model the final brightness with start brightness and peroxide dosage. As the start brightness is relatively steady with under 1,0 STDEV and COV, it is possible to only use the peroxide dosage when modelling the final brightness. In this linear regression model there only the correlation of the amount of peroxide was analyzed. End brightness and the results can be seen in table 13.

TABLE 13. Modelling the effect of peroxide to final brightness under 20 kg/ton

Multiple R	R Square	Intercept (Start brightness)	X Variable (Peroxide)
0.874	0.859	69.760	0.281

From here can be seen that the gain in H_2O_2 dosage to final brightness in low peroxide dosage is 0,281, where the Y is one value of ISO % - brightness and X

– value is peroxide. This means that 1 kg/adt of peroxide will increase the end brightness of the pulp by 0,281 ISO %.

After the low level peroxide – modelling the same was done to the higher-level peroxide. The higher brightness target resulted in the average of 31,3 kg peroxide for one ton of pulp as shown in table 14.

TABLE 14. Modelling the effect of peroxide to final brightness over 30 kg/ton

Multiple R	R Square	Intercept (Start brightness)	X Variable (Peroxide)
0.937	0.878	71.323	0.179

This means that the gain in H2O2 dosage to final brightness in high peroxide dosage is 0,179, so 1 kg/adt will increase the brightness 0,179 ISO %.

Then coefficients are used to calculate the brightness gain response for the H2O2. Figure 17 illustrates the non-linear brightness gain in response to peroxide dosage.

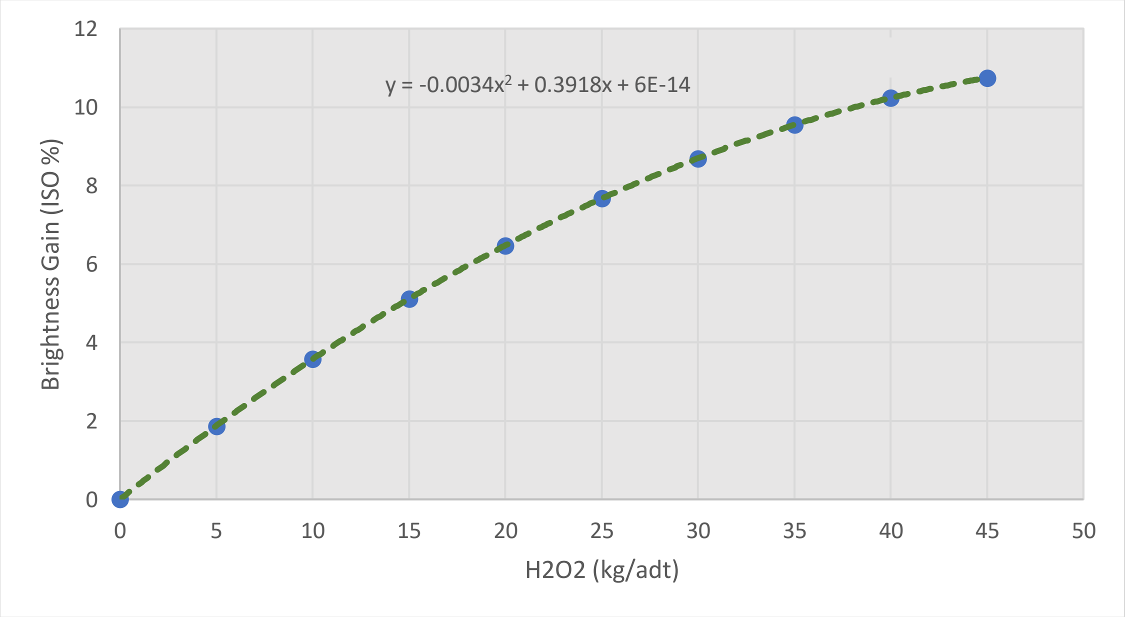


FIGURE 13. Brightness gain in response to Peroxide dosage

With this information it is possible to calculate how much less peroxide should be used to acquire the lower ISO % brightness target of 73 ISO % when the average brightness in the process is 74,2 ISO % and with the higher brightness target of 77 ISO % the actual average is 77,8 ISO %.

The current levels for H2O2 – dose are 16,3 kg for every ton of lover brightness pulp and 31,3 kg for every ton of higher brightness pulp. Following the gain model it can be calculated, that by reducing both the lower and higher brightness H2O2 dosage by 3 kg per ton the mill would still be able to keep the average brightness above the target.

8. RESULTS AND SUMMARY

The object of the thesis was to study the BCTMP-process, its mechanisms and raw material and hardware behavior within the BCTMP-process and the affect of refining and bleaching on the final product qualities. The theoretical part of the thesis gave the ability to understand the fundamentals of the pulp manufacturing process and to give tools for the experimental part to find the potential bottlenecks and process steps that made overquality. From the mill-DCS data the goal was to obtain the required information of the refining and bleaching processes to develop more efficient operating models via modelling the historical data of refining energy, freeness, fiber length as well as chemical consumption and brightness.

When studying the process data, correlations were found that showed that the mill processes can be operated more efficiently. Considering the large variations in the process, the full potential cannot be achieved with only operating the process more carefully, but there should be investments made into the control systems of the mill to stabilize the process values. If these investments are not made, the calculated savings potentials for the process will decrease substantially.

Regarding the BCTMP-mills refiners, it was shown it is possible to decrease the average refining energy by 54 kWh/adt throughout the year without exceeding the mills current freeness target as seen in figure 14. With the energy price (2020 Nord Pool Spot avg.) of 0,055 €/kwh and with the annual production of 160 000 ton this would mean total energy savings of 475 000 €, illustrated in figure 15

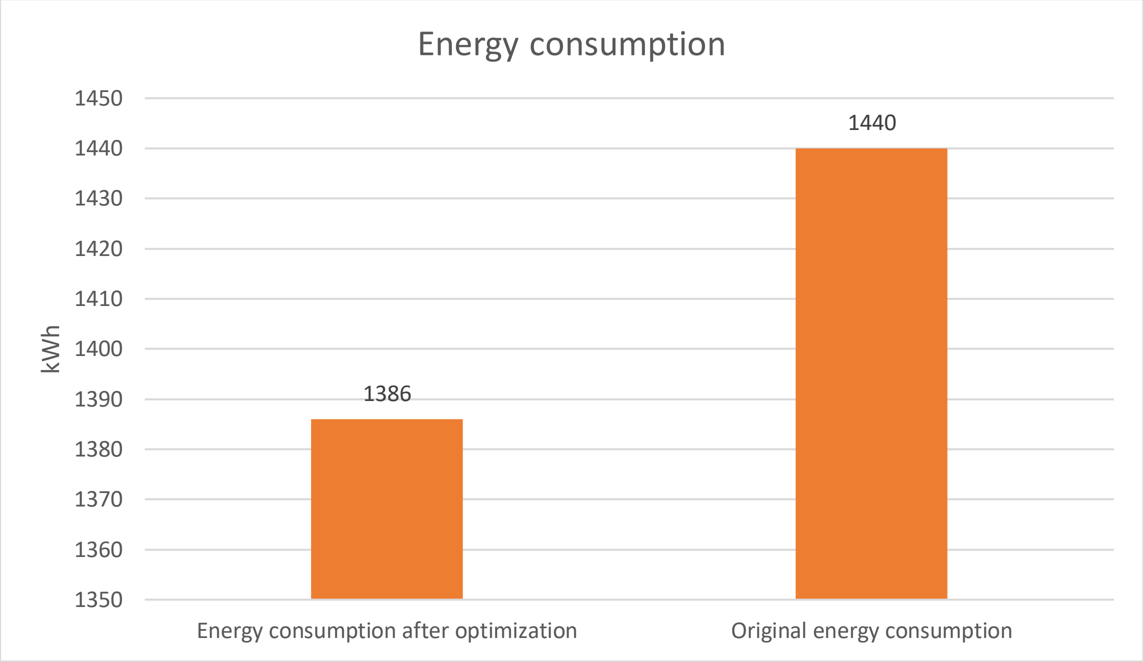


FIGURE 14. Refining energy consumption before and after optimization

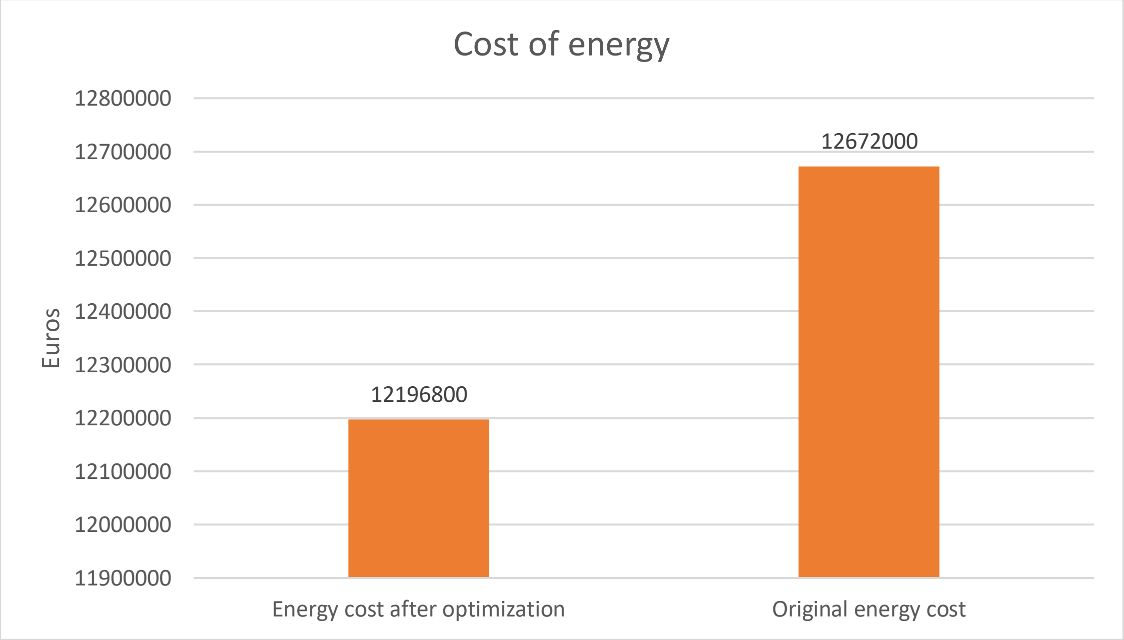


FIGURE 15. Refining energy cost comparison before and after optimization

When reviewing the peroxide bleaching part of the process, the study showed that it is possible to decrease the peroxide consumption by 3 kg/ton on average as illustrated in figure 16. This combined with the H2O2 price of 0,485 €/kg and the 160 000 ton annual production means, that the total chemical savings for one year would be 232 000 € as shown in figure 17.

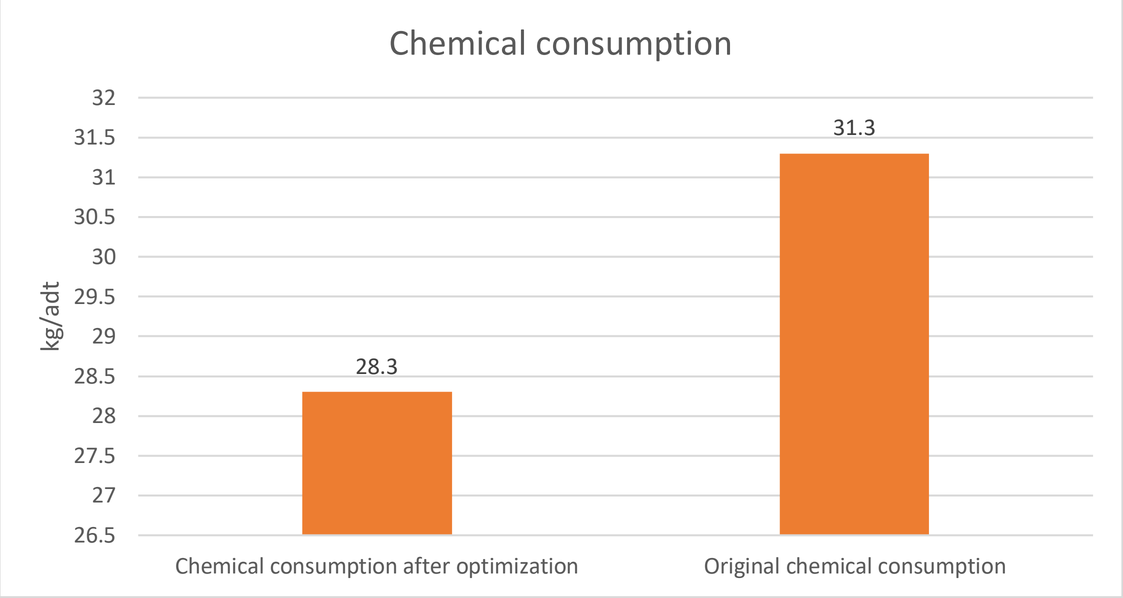


FIGURE 16 Chemical consumption before and after optimization

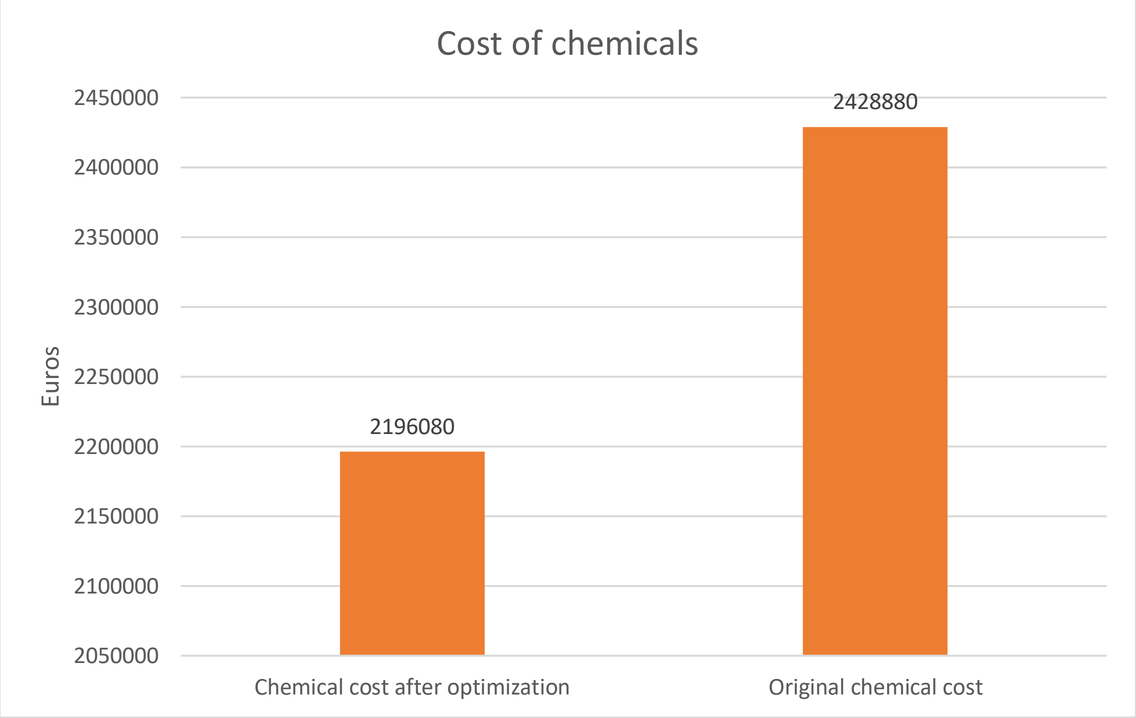


FIGURE 17. Chemical usage cost comparison before and after optimization

In total if the process would be stabilized, the operators could run the process closer to the target quality and save over 700 000€ per year in both refining energy costs and chemical consumption costs.. In the current situation it is also possible to achieve savings by teaching the operators and supervisors to focus more on the product target quality and trying to control the process closer to the economic optimum. Not only to refine and bleach excessively but to try to make the required quality for the most economically beneficial way. In order to achieve the savings, the mill leadership has to commit all the shifts into meeting the production targets with in-spec quality consistently and minimize as well as the different operating models between shifts as well as human errors.

Incorporating data analysis to the tool set of every pulp and paper mill development organization will be a valuable method as the mills want to push costs down to stay competitive and the customers want to have proof that their products have been made as sustainably as possible. This study will open up the academic discussion of for additional operational savings in mills that are already operational based on data. When the industry finds these topics interesting the further studies for additional cost savings will be to analyze the water removal efficiency in the process by optimizing the different dryers in the process and eventually optimizing the press- and drying sections of paper machines for the most cost efficient water removal. In the chemical pulping side there are also many possibilities for further studies, for example saving energy by minimizing cooking temperature and optimizing the average kappa-level to make the process more stabile.

Data-analysis methods are beneficial to every mill in the world since they help to understand how the costs form in the mill, what is important for the customer regarding the product and how to get the most out of the machinery, raw-material and personnel the mill has in its disposal. These are all critical stakeholders when the cultural change has to be transferred from the board room to the factory floor with a up-to date change management methods with lasting effect.

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