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ASSESSMENT AND ENHANCEMENT OF THE PERFORMANCE OF THE PULP WASHING OPERATION IN KRAFT MILLS

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ASSESSMENT AND ENHANCEMENT OF THE PERFORMANCE OF THE PULP WASHING OPERATION IN KRAFT MILLS

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DEDICATION

To my parents, Melchor and Hilda

for their encouragement and support.

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RESUME

Le secteur industriel des pâtes et papiers est un des piliers de l'industrie du Canada. Il est également un des plus gros consommateurs d'énergie et d'eau et la facture énergétique associée est généralement comprise entre 25 et 50 % de la totalité des coûts de fonctionnement pour ce type d'usine. Le secteur industriel papetier du Canada a été durement touché par la crise financière de 2008, ainsi que par une stagnation de la consommation de papier en Amérique du Nord. Si on ajoute à cela la concurrence des pays émergents comme l'Inde, le Brésil et la Chine, dotés d'usines plus récentes, l'industrie papetière canadienne traverse aujourd'hui sa plus grande crise depuis sa création, il y a 200 ans.

Il existe trois procédés différents pour obtenir la réduction de la biomasse en pâte à papier. La voie chimique, la voie mécanique et la voie semi-chimique. Ce projet porte uniquement sur un procédé de fabrication par voie chimique, connu sous le nom de procédé Kraft. Ce procédé est le plus employé et représente 75 % de la production mondiale de pâte. Afin de rester compétitives, les usines doivent accroître leur efficacité énergétique pour mieux contrôler leurs coûts de production. Les équipements employés pour préparer la pâte Kraft sont des gros consommateurs d'eau et d'énergie, lorsqu'ils ne sont pas correctement optimisés. L'analyse de la performance de ces équipements est une étape importante qui précède toute technique d'optimisation par l'analyse des procédés. Si les résultats de cette opération sont concluants, on peut alors envisager des modifications dans les conditions de fonctionnements des équipements. Ce type de mesure nécessite peu d`investissement et s`avère être une source d`économie significative.

Dans le procédé, certains équipements jouent un rôle central et il est important d`en évaluer la performance afin de proposer les modifications nécessaires à assurer leur fonctionnement optimal. Du point de vue de la consommation d'énergie, les équipements considérés sont les laveurs, les évaporateurs, les chaudières et les sécheurs. Les laveurs sont les équipements qui consomment le plus d'eau et ils ont un impact direct sur la consommation de vapeur dans les évaporateurs. En effet, l'eau de lavage est ensuite envoyée aux évaporateurs pour atteindre un certain niveau de concentration en matières solides dissoutes. Les laveurs situés dans les départements de lavage de la pâte brune et de blanchiment utilisent en moyenne 74 % de l'eau totale consommée dans les usines construites dans les années 1980. La consommation moyenne de vapeur dans les blanchisseurs et les évaporateurs représentent à eux deux 42 % et 47 % de la

consommation totale de vapeur des usines qui emploient respectivement des feuillus et des résineux.

On trouvera dans cette étude l`analyse de performance des laveurs pour trois usines canadiennes. Par soucis de confidentialité, ses usines seront nommées usines A, B et C. Cette étude comprend la description des différents départements de l'usine, la validation du modèle numérique de l'usine, la caractérisation et la comparaison des résultats obtenus avec la moyenne nationale. On trouvera également une description générale des usines B et C. Dans cette étude, la performance des laveurs est caractérisée à l'aide de trois indicateurs, le premier est un paramètre appelé « Equivalent Displacement Ratio » (EDR), le second est le taux de matières solides dissoutes extraites durant le lavage et enfin, le troisième est l'efficacité du lavage. Un diagnostic de performance des équipements ainsi que des projets visant à accroitre leur efficacité sont proposés dans cette étude pour atteindre une réduction de la consommation d'eau comprise entre 3,4% et 49%, et une réduction de la consommation de vapeur comprise entre 1,8% et 7,6%, selon les usines.

ABSTRACT

The pulp and paper industry is one of the highest energy consumers amongst all industry in Canada, with energy costs between 25% and 50% of the total cost of product. The Canadian pulp and paper industry has also been facing a stagnation in the demand in the pulp market over the past few years, and emergent countries with modern mills are creating strong competition for the old Canadian pulp and paper industry. There are three types of pulping processes, chemical, mechanical, and semi-chemical pulping. This project focuses only on a specific chemical pulping method known as Kraft pulping process, representing 75% of chemical pulping in Canada. In order to stay competitive, the Canadian pulp and paper industry has to improve the energy efficiency of their mills and decrease energy costs.

Analyzing the performance of process equipment is an important step prior to any process integration technique, since equipment items with poor performance can increase the energy and water demand of the overall process. Analyzing the equipment performance results in finding the inefficiencies which can be resolved by modifying the operating conditions or control strategy (low investment projects) or changing equipment in the case of design problems (high investment project). Analyzing the performance of some key equipment is more essential regarding energy and water consumption to evaluate their performance and propose modifications in order to adjust their operation in comparison to typical or even best practice range of operation. These key equipments are washers, evaporators, boilers, and dryers.

Washers are a major water consumer and their efficiency also has a direct effect on the steam consumption of the evaporators. In the brown stock washing and bleaching department, washers account for almost 75 % of water consumed in a typical Canadian mill built in the 1980's. The median amount of steam consumed in bleaching and evaporation represent 42% and 47% of the total steam consumption in Canadian mills for hardwood and softwood, respectively.

In this study, washing performance analysis was done for three Canadian partner mills. For confidentiality purposes mills were referred to as A, B and C. For mill A, a study regarding process description per departments, validation of the simulated model, characterization and benchmarking was done. For mill B and C, a general description of the mills was addressed. One efficiency parameter, equivalent displacement ratio (EDR), was selected as the best indicator and benchmarked for all washers. The EDR, which represents the percentage of solids removal, and the washing efficiency were calculated. A diagnosis of the key equipment was performed and water and energy projects were proposed, reaching water savings from 3.4 % up to 49 % and steam savings from 1.8 % to 7.6%.

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NOMENCLATURE

Symbol	Description	Units
EPA	Equipment performance analysis	dimensionless
PI	Process Integration	dimensionless
GHG	Greenhouse gases	dimensionless
BOD	Biological organic demand	[mg/l]
COD	Chemical oxygen demand	[mg/l]
GJ	Giga Joules	[GJ]
odt	Oven dried ton	[ton]
adt	Air dried ton	[ton]
TCF	Total Chlorine Free	dimensionless
ECF	Elemental Chlorine Free	dimensionless
RVD	Rotary vacuum drum	dimensionless
CBF	Compaction Baffle Filter	dimensionless
Ds	Dissolved solids	percentage
KPI	Key performance indicators	dimensionless
APE	Alkyl phenol ethoxylate-free	dimensionless
AOX	Absorbable organic halides	dimensionless
NIM	Non isothermal mixing points	dimensionless
DCF	Discharge correction factor	dimensionless
Cd	Discharge consistency	percentage
ICF	Inlet correction factor	dimensionless
DD	Drum displacer	dimensionless
PD	Pressure displacer	dimensionless

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CHAPTER 1 INTRODUCTION

1.1 Context

The pulp and paper industry is one of the highest energy consumers amongst all industry in Canada. Its energy costs are between 25% and 50% of the total production costs, like the cement and lime industries. The Canadian pulp and paper industry has also been facing a stagnation in demand in the pulp market over the past few years, and emergent countries like China, Brazil and Indonesia, with modern mills, are creating strong competition for the mature Canadian pulp and paper industry, as seen in **Figure 1-1**.

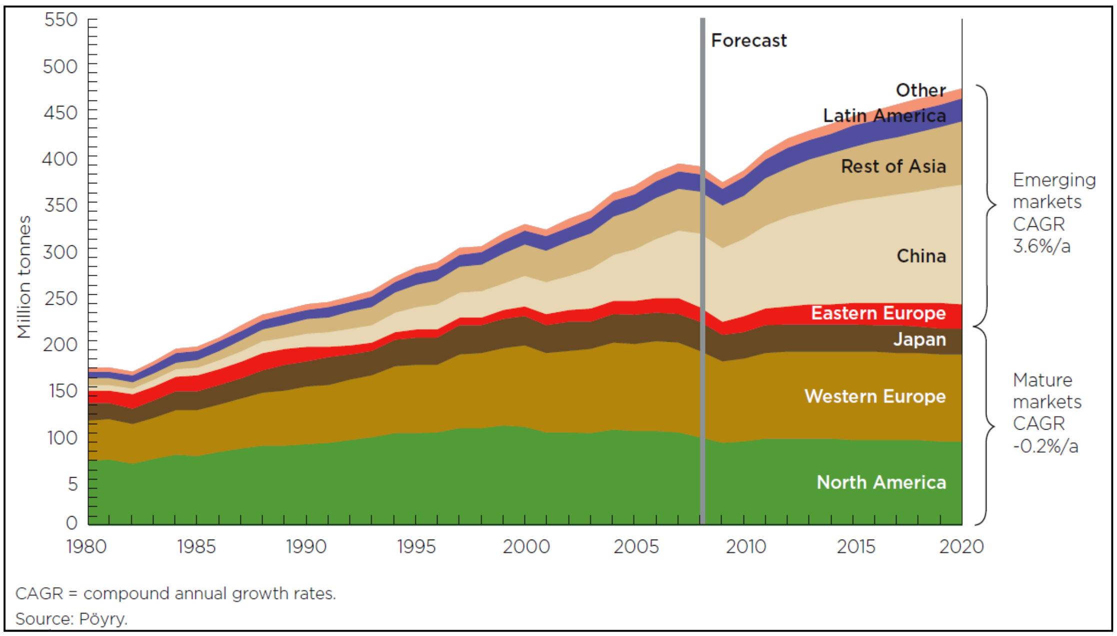

Figure 1-1: Global demand for paper from 1980 to 2020 used by permission of Poyry. (Commonwealth of Australia, 2010)

There are three types of pulping processes; chemical, mechanical, and semi-chemical pulping or hybrid. This project will focus only on the specific chemical pulping method of Kraft pulping. Almost 75% of all pulping processes is chemical pulp, and from the chemical pulping the highest fraction is made via the Kraft process.

In order to help stay competitive, the Canadian pulp and paper industry has to improve the energy efficiency of their mill and decrease energy costs.

Due to the complex and interdependent nature of pulp and paper mills, sometimes simple models are not enough to optimize the system. In these cases, where overall system optimization is desired, it is required to use simulation software that can capture the interdependent nature of the system.

Analyzing the performance of process equipment is an important step prior to any process integration technique, since equipment items with poor performance can have high energy and water demand. If after the analysis of equipment performance there is no problem with equipment design, basic modification of operating conditions or control philosophy can be looked at to improve performance, which is an inexpensive, low investment approach.

There are some key equipment items in the process for which it is important to evaluate the performance and propose modifications so that they work in a typical or even best practice range of operation. For the focus on energy performance, the identified equipment items are washers, evaporators, boilers, and dryers. Washers are a major water consumer and they also have a direct effect on the steam consumption of the evaporators. Washers in the brown stock washing and bleaching department account for 74% of the water consumed in a typical Canadian mill built in the 1980's (Chandra, 1997). The median amount of steam consumed in bleaching and evaporation accounts for 42% and 47%, for hardwood and softwood, respectively, of the total steam consumption in Canadian mills (CIPEC, 2008).

This work will focus on the washing performance analysis of three Canadian Kraft mills. For confidentiality purposes they will be referred to as mill A, B, and C.

1.2 Justification

Current energy and water optimization process integration techniques do not consider the individual performance of the equipment. The addition of equipment analysis to any process integration technique will improve the water and energy savings. Washers are one of the bottlenecks of the Kraft process typically ignored in energy efficiency studies; even washing in brown stock and in bleaching has a high impact on the water and energy consumption of the mill.

1.3 Plan of the thesis

In chapter II, the literature review will be presented. In the first part of the chapter, the equipment performance analysis and benchmarking will be shown.

In chapter III, the Kraft pulp washing will be presented. It will show the Kraft process, by department, and the characteristic energy and water consumption will be described. Equipment performance-analysis and its significance will be highlighted in general and specifically for washing.

In chapter IV the methodology applied to this work will be described. An overview of the methodology in a flow diagram will be presented as well as an in-depth description of each stage and its role in testing the hypothesis. The simulation and validation method of the partner mill, which includes a mill description and a validation of the simulation in Cadsim Plus® will be explained. The energy system characterization, water and steam networks, temperature, and consistency along the pulp line will be shown, as well as how they relate to the process benchmarking. An explanation of the equipment performance analysis method used for washers and the method for then generating energy and water saving projects will be shown.

In chapter V, case studies of the Kraft mills will describe partner mill A, and give brief descriptions of partner mills B and C. For mill A, a mill description, presentation of the simulation model and validation will be presented, which includes a mill description and a validation of the simulation model in Cadsim Plus ®. A characterization of the partner mill, including the water and steam network, temperature, and consistency along the pulp line, water and steam consumption and effluent production as process benchmarking will be shown. Finally a brief description of mill B and C will be added, identifying the applicable parts of the methodology and results from mill A.

In chapter VI the results of the washing performance analysis for the three mills will be presented. The main results are the washer characterization for each mill, the calculation of the key performance indicators (KPI) for brown stock washing, and benchmarking against the typical KPI values. The diagnosis and project proposals to enhance washing performance and water reduction will then be presented, linking back to the analysis.

In chapter VII the conclusions, recommendations are presented.

CHAPTER 2 LITERATURE REVIEW

The background and literature review explanations are divided in several parts; the first part is the description of the energy system analysis and finally the equipment performance analysis and summary of the literature review chapter are given.

2.1 Equipment Performance Analysis (EPA)

Navarri & Bernard (2008) suggested energy audits of specific equipment and benchmarking them against typical values in combination with process integration technique in the food industry. Energy savings can also be reached by modifying operating conditions and project identification (CanmetENERGY, 2003). Optimization in the process, such as tuning boilers, checking appropriate insulation thickness, identifying and repairing steam traps, identifying streams that are cooled down and heated, and eliminating redundancy, monitoring excess furnace air, etc, can also produce energy savings (Elshout & Marchant, 2010).

Key performance indicators, when used efficiently and against benchmarking, can trigger the areas and equipment that have opportunity savings, in a fast way. There are already existing key performance indicators for most of the key equipment items, including the evaporators, dryers, boilers and washers. For the evaporators and dryers, the key performance indicator used is the economy. It represents the mass of evaporated water per mass of steam consumed. The savings for evaporators can help to be increased by vapor recompression and/or using the heat of other parts of the process (Beagle, 1962).

For washers, there are also many key performance indicators, such as the displacement ratio, DR, equivalent displacement ratio, (EDR), the Norden efficiency factor, (E), the modified Norden efficiency factor, (E_{st}) (Crotogino et al., 1986; Luthi, 1982; Miliander, 2009a; Stromberg, 1991). These parameters will be explained in detail in the next section. Washers are one of the bottle-necks of the Kraft process typically ignored in energy efficiency studies, however they are an important item as they are the highest water consumer in the process. The performance of the washers can directly affect the steam consumption of the evaporators and other parts of the process.

Several approaches used to improve brown stock washing and reduce carryover of black liquor to the bleach plant include increased shower flow, additional shower bars, and addition of defoamer and washing aid chemicals. Bennett (2000) and Chisholm (1998) studied CO_2 addition to the shower flow in order to decrease water consumption due to the acidification in the shower flow. This helped by decreasing the swelling of the fibers, making the washing easier, and reducing the water consumption by around 10%. New chemical technologies, like the use of alkyl phenol ethoxylate-free (APE), help to decrease the organic and inorganic carryover, improve washing, increase the mat formation, and require lower shower flows. It is reflected by a decrease of 15-20% of absorbable organic halides (AOX), which consumes 10-25% of the chlorine and also reduces the formation of dioxin- type chemicals (Barton et al., 1997).

A survey of the washing efficiency parameters in Canadian bleach plants found which variables are most used to evaluate parameter performance. The main parameters measured were the pH in the mat liquor, the soda carryover, COD, and conductivity (Towers & Turner, 1998). Kopra et al. (2008), studied the refractive index as a measurement of wash loss. The wash loss is a measurement of efficiency in practice, and it represents the amount of sodium in the pulp before and after being washed. According to Sillanpää (2005) the COD is not adequate as a measurement of the washing loss in bleaching, but in brown stock washing according to Noel et al., (1993) there is a linear relationship between conductivity and COD, which is analogous to the washing loss.

According to Lunn (2001) soda can be a good measurement of the washing efficiency if the data for soda balances is available. Other mineral species used to measure the washing efficiency are: Mn, Ca, Si, Fe, and Cu. A trial was done at Celgar Pulp and it found no difference between the inlet and outlet of calcium and silicon (Lunn, 2001).

The effect of filtrate washing configuration was studied by Antkowiak (2000), who found that by dividing the filtrate of the washer formation zone, the filtrate with less concentration of solids was used to dilute the feeding pulp to the washer, thereby increasing the washer efficiency.

Process control is another cost effective approach for improving washer efficiency. Sufficient filtrate surge tank capacity is recommended to balance accumulations in pulp storage tanks, especially during production-rate changes, (Noel, et al., 1993; Wasik, Mittet, & Nelson, 2000).

2.2 Process Benchmarking

The use of key performance indicators and benchmarking allows users to identify the departments with opportunity areas due to inefficiencies in the process, such as non-isothermal mixing (NIM) points, which can be classified as process to process, water to process and water to water. There exist key performance indicators for processes, equipment, and tools to identify NIM points in the process, such as the temperature and consistency along the pulp line.The overall key performance indicators for the process are water consumption per air dried ton, effluent production per air dried ton, and energy consumption per oven dried ton.

Energy Benchmarking

The energy benchmarking methodology developed by the Pulp and Paper Research Institute of Canada (Paprican) compares the energy use by mill and by unit operation. This benchmarking considers 24 Kraft mills of the 49 total mills in Canada. The benchmarking information includes energy consumption and production, net thermal energy for recovery boilers and thermal energy consumption, by manufacturing areas, common areas and product. Also included are the fuel consumption of boilers in manufacturing areas and the electricity consumption for common areas and manufacturing areas. The tables showing these benchmarks can be found in appendix 3. The information is categorized in 25th percentile, median, 75th percentile and modern mills.

Water consumption

Average water consumption was calculated according to Chandra (1997). The water consumption for mills was categorized in three ways: the older mills (1960s), the newer mills (1980’s), and for the mills currently being built, which means mills designed in the 1990’s.

<u>Effluent production</u>

Similarly for water consumption mills were categorized in the same three ways: the older mills (1960's years), the newer mills (1980's), and the mills currently being designed, which means mills designed in the 1990's (Turner et al., 2001).

<u>Temperature and consistency along the pulp line</u>

These tools identify all the water and white water dilution points along the pulp line and their impact on the temperature and consistency in the fiberline. An increment in the temperature represents a steam injection, a decrement of the temperature represents an addition of fresh water or white water from the process (Savulescu & Alva-Argaez, 2008). Inefficiency can be found if dilution is carried out and then steam injection is done afterward. Such a situation can be a redundancy increasing the energy losses.

For better results, it is crucial to include information regarding specific temperature and consistency constraint levels in the department, or the manufacturing area where the temperature constraint is valid. Departments that usually have temperature constraints are the brown stock and bleaching department, where chemicals can have optimum temperature conditions.

2.3 Summary

Energy audits for specific equipment items and process integration were done for food industry but not for pulp and paper industry. Some modifications in the process can be done to increase the energy efficiency such as: tuning boilers, identifying and repairing steam traps, identifying streams that are cooled down and heated and eliminating redundancy, and monitoring excess furnace air. Benchmarking for the most important department can expose the department with opportunity areas, after which key performance indicators can be calculated for the equipment in the department with opportunity areas, such as evaporators, dryers, boilers and washers. For the washers that are in brownstock and bleaching, they represent almost 75 % of the water consumed in the mill and around 45 % of the steam consumption in bleaching and evaporation. The main key performance indicators for washers are the displacement ratio, DR, equivalent displacement ratio, (EDR), the Norden efficiency factor, (E) and the modified Norden efficiency factor, (E_{st}).Improvement in the washing efficiency can be done by increasing the shower flow, the addition of shower bars and the addition of defoamer and washing aid chemicals.

The reutilization of the different quality of the filtrates produced in different zones of the drum in the drum displacer can be used to increase the washing efficiency by using the filtrates with less concentration of solids to dilute the feeding pulp to the washer. Process control can also be used to increase the washing efficiency due to the fact that the mills most of the times do not have adequate levels of control.

CHAPTER 3 OBJECTIVES

General objectives

- To evaluate the performance of the washer equipments in three partners mills.
- To increase the energy efficiency in a Kraft mill by modifying the operating conditions and improving the performance of washing equipment.

Sub-objectives

- To perform a benchmarking for the energy and water system globally, by department and for specific equipment.

CHAPTER 4 KRAFT PULP WASHING

The chapter consists in two parts. The first part presents a brief explanation of Kraft process, the second part is the description of definitions of washing in Kraft, key performance indicators, types of washer, variables affecting washing, typical values for key performance indicators and a brief conclusion of the chapter.

4.1 Kraft Process

The Kraft or sulphate process was developed by Carl Dahl in 1884. The name of the process comes from the German word “Kraft,” which means "strong" or "power". The Kraft process and sulphite process are both chemical pulping processes. There are two other types of pulping processes, mechanical and semi-chemical pulping or hybrid. This project will focus only on the Kraft process.

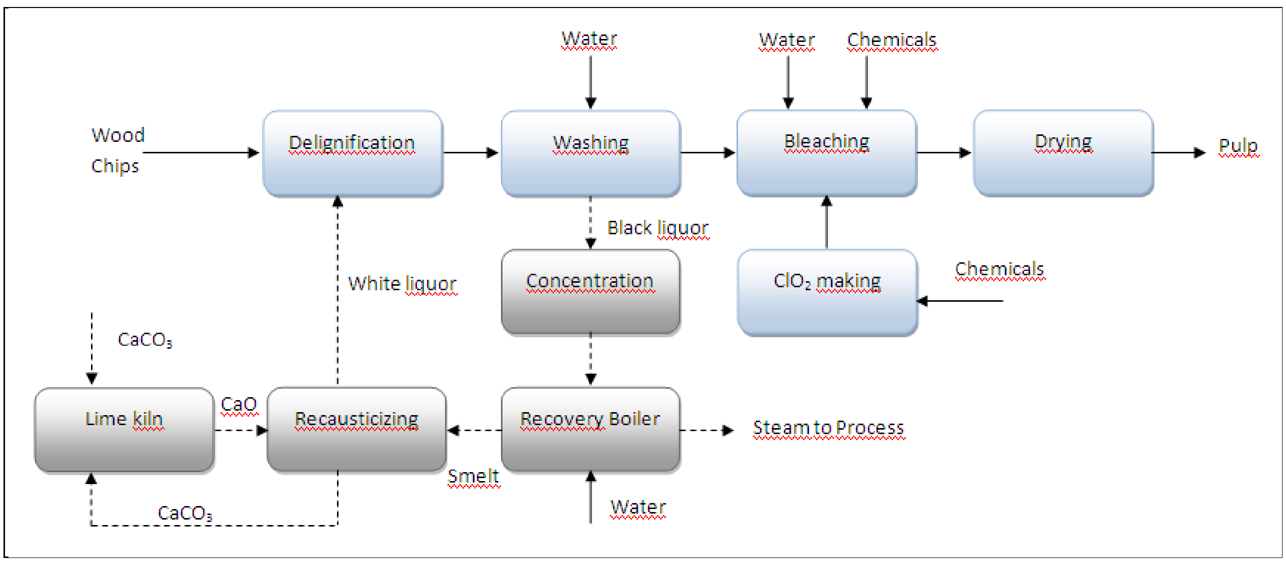

Figure 4-1: Simplified Kraft process based on (Mateos-Espejel et al., 2011)

A typical Kraft mill uses wood chips, water, fuels (natural gas, bark, oil) and chemicals to produce pulp and paper, steam, and electricity. The main components of wood are cellulose (40-47%), hemicelluloses (25-35%), lignin (16-31%), and extractives (2-8%) (Smook, 1994). Wood can be divided into two general classes: hardwood and softwood. Softwood trees are conifers, having the characteristic of long fibers, which provide strength to a sheet of paper. Some examples of softwood are pine, spruce, and fir. Hardwood gives higher brightness because they have less lignin than softwoods, with some common examples of hardwood being aspen, birch, and maple.

The Kraft process is divided into two major lines, the fiber line and the chemical recovery loop. The main sub-processes of the fiber line are the preparation stage (debarking, chipping, and screening), delignification, washing and screening, bleaching, and drying. The main sub-processes of the chemical recovery loop are evaporation, recausticizing, and the recovery boiler.

4.1.1 Preparation

The raw material for the Kraft process consists of wood logs and wood residues from sawmills. Firstly, the bark and dirt are removed before the cooking process. There are two common types of debarking: dry and wet. The main reason why mills prefer dry debarking is the high discharge of biochemical oxygen demand (BOD) that is produced as an effluent with wet debarking. Another disadvantage of the wet debarking is the increase in the moisture content of the bark, which reduces the efficiency of energy recovery. Typical effluent volumes for a wet debarking system are between 0.5 – 4.0 m^3/adt (air dried ton) and close to zero for a dry debarking operation (Asblad et al., 2001). Steam or hot water is used in cases where thawing is required. Debarked logs are reduced to small fragments in chippers to ensure a homogeneous size for the cooking process; screens are used to separate the fines and oversize chips.

4.1.2 Delignification

After the debarking and chipping stage, the wood chips are cooked or digested with steam in the digester, which is a chemical reactor. The objective of the delignification process is the removal of lignin without affecting the quantities of cellulose and hemicelluose. A solution of NaOH and $NaS_{2,}$ called white liquor, is used for delignification, typically at a concentration of 100 – 110 g/L. The cooking can be done either via a continuous or a batch process. The average water consumption is 1 m^3/adt, which is independent of the type of cooking or delignification process (Chandra, 1997).

Continuous digesters

In a continuous cooking digester the chips and white liquor are fed into the top of the digester at a continuous rate. There are two types of continuous digesters; the single vessel and the two vessel type. The main difference between them is that in the single vessel digester, the impregnation occurs in the upper part of the vessel, and in the second vessel digester, it occurs in the first vessel prior to the second main digester vessel. Heating can be done by indirect steam heaters or with direct steam application. The injected cooked pulp is washed in the lower part of the digester in the washing zone, where the water displaces the cooking liquor (black liquor) from the pulp. The black liquor is then flashed to increase the dissolved concentration and this steam can be used in the steaming vessel. The median steam requirement for a continuous digester for Canadian mills is 1.7 GJ/odt (CIPEC, 2008).

Batch digesters

In batch cooking, the digester is filled with chips and uses direct steam to heat them before the cooking liquor is introduced. A batch digester plant consists of several batch digesters working in different phases to ensure a continuous supply for the process. The median live steam requirement for a digester for a Canadian mill is 4.8 GJ/odt (CIPEC, 2008)

The cooking is completed once the lignin is dissolved, and the remaining cellulose and hemicellulose is called pulp or brown stock. The next operation of the process is the washing and screening stage, in which the pulp will be separated from the lignin.

4.1.3 Brown Stock Washing and Screening

Washing is the operation in which dissolved impurities in the brown stock are removed. This process is important for the fiber line because if the washing is well done, the pulp will require less chemical addition in the bleaching stages. In the chemical recovery loop, it is crucial to have high separation efficiency in the washing due to the extraction of the dissolved organics and inorganics that will be sent to the recovery boiler to produce steam and power. Typically, the weak black liquor that comes out of the washers has a concentration of 10-15% of dissolved solids (CHSI, 2011).

Although the washing can be improved by adding more water like a shower flow, it will have a negative effect on evaporation and chemical recovery. In the evaporation department, a decrease in the concentration of dissolved solids in the weak black liquor will have a negative effect on the steam consumption, requiring more steam to remove water and deliver the required high solids content black liquor to the recovery boiler.

The screening section can be done before or after the brown stock washing; the objective of this process is to remove the fine and oversized pieces of wood. The most common equipment used for screening is screeners and knotters.

In continuous digesters, the first stage of washing is performed in the digesters, unlike the batch process where the first stage of washing is carried out in the brown stock washing section.

The average water consumption for continuous digesters is 1.8 m^3/adt according to Chandra (1997), and there is zero steam consumption in this area.

4.1.4 Bleaching

The objective of bleaching is to improve the brightness and cleanliness of the pulp, with the help of chemicals. Bleaching is carried out in stages in towers and washers, with the addition of different chemicals between stages. Typically, bleaching has been performed with chlorine-containing chemicals, like elemental or gaseous chlorine (Cl), hypochlorite (H) or chlorine dioxide (D). Between stages, the dissolved lignin is extracted with alkali (NaOH).

Table 4-1: Bleaching chemical stages definitions based on (Paper on Web, 2011)

Symbols	Bleaching stage	Description
A	Acid treat.	To remove metal element from pulp.
C	Chlorine	Elemental chlorine (Cl_2) is an effective de-lignifying agent. As it breaks the lignin chain it produces chlorinated organic material.
D	Chlorine dioxide	Chlorine dioxide (ClO_2) is an extremely selective chemical that can de-lignify and brighten pulp, but it can produce chlorinated organic material.
E	Alkaline extraction	To remove colored components from bleached pulps that has been diluted with a warm alkali solution.
H	Hypochlorite	Sodium hypochlorite (NaOCl) is inexpensive low cost de-lignifying agent formed by mixing elemental chlorine Cl_2 with NaOH at mills.
O	Oxygen	Oxygen removes lignin and modifies other coloring components.
P	Hydrogen peroxide	Hydrogen peroxide (H_2O_2) is used to brighten pulps in the final bleaching stages, prevents the pulp from losing brightness.
Q	Chelating stage	To control brightness from other heavy metals and iron salts, by washing the pulp with chelating agents like EDTA. Lower pH solution are more effective at removing transition metals .
W	Treat.with water	Wash between stages to remove the chemicals between stages.
X	Enzyme stage	Enzymatic pretreatment in a TCF (Totally Chlorine Free) sequence used for an easier bleaching and delignification of the pulp. It acts in alkaline pH and high temperatures, which provokes the breakage of the xylan polymers in pulp fibers that tightly linked to cellulose and lignin, extracting the lignin from the pulp.
Y	Sodium Hydrosulfite	Good for recycled fibers.
Z	Ozone	Good to brighten the pulp and as a delignification agent.

Bleaching sequences use a combination of different chemicals. In the USA, Canada, and Europe, the use of elemental chlorine has been almost totally discontinued. Two categories of bleaching stages used are ECF (Elemental Chlorine Free) and TCF (Total Chlorine Free). Chlorine dioxide is used in ECF, while in TCF it is not used at all. The bleaching sequence and the number of stages depend on the brightness that is required for the pulp.

The median live steam requirement is 3.4 GJ/odt for softwood bleaching and 2.33 GJ/odt (NRCan, 2008) for hardwood bleaching. The average water consumed in the acid stages is 21 m3/adt, and 10 m^3/adt for the alkaline stages (Chandra, 1997). The average effluent flow for mills in a current design for acid stages is 10.5 m^3/adt, and for alkaline stages is 10.6 m^3/adt (Turner et al., 2001).

4.1.5 Drying

Finally, the pulp is drained, pressed, and dried in a pulp machine. The drying unit operation is composed of two sections, the wet end and the dryer section .The wet end section is comprised of a head box, forming table, wire presses and press section, which remove water from the fibers through mechanical means of gravity, vacuum draining and physical compression. The dryer section is comprised of a series of steam heated cylinders, which contact the running pulp web and evaporate water from it. Ventilation is used to enhance the water removal and a heat recovery system is used to recover heat from the humid exhaust air. The dryers consume approximately 23% of the energy of the Kraft process according to consumptions of CIPEC (2008). It is therefore highly desirable to maximize water removal in the wet end section where the cost is much lower.The median steam consumption for a pulp machine is 4.33 GJ/adt (2008). The average water consumed is 4.9 m^3/adt (Chandra, 1997). The average amount of effluents is 4.9 m^3/adt (Turner et al., 2001) .

Chemical Recovery Loop

To improve the economy and the environmental performance of the mill, recovery of the white liquor from black liquor is highly desirable. Traditionally, black liquor was recovered only to provide savings in chemical consumption, but in modern mills, energy is also recovered in the process, in order to make it even more economical. In this respect, a significant amount of steam is produced in the recovery loop. The recovery loop starts when the black liquor is separated from the fiber. Black liquor is dark in color and is composed of dissolved lignin, hemicelluloses, sodium compounds, and sulfur based products used in the delignification process. The process in the chemical recovery loop can be seen in **Figure 4-2.**

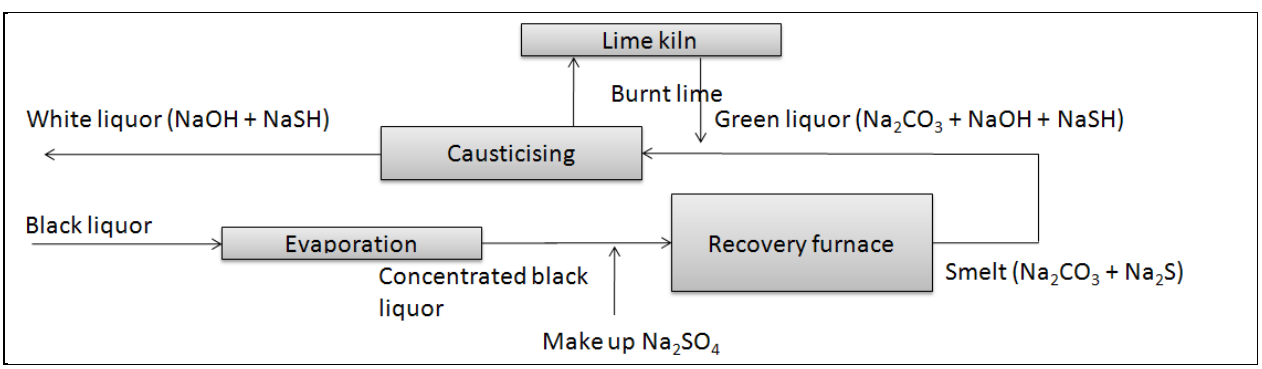

Figure 4-2: Steps in the chemical recovery loop based on Brännvall, (2009)

The black liquor is first increased in concentration through evaporation, energy is then recovered from the organics portion of the liquor and, finally, the remaining inorganics are kilned and causticized to produce fresh white liquor.

4.1.6 Evaporation

The washing filtrate (black liquor) produced in the brown stock department is pumped to the evaporation plant to increase the concentration of dissolved solids to about 70%.

The median steam consumption for an indirect contact evaporator train is 5.9 GJ/adt and for a direct contact evaporator train it is 2.95 GJ/adt (CIPEC, 2008) . The average water consumption is 0.6 m^3/adt (Chandra, 1997) , and the average effluent production is 0.4 m^3/adt (Turner et al., 2001).

4.1.7 Recovery boilers

The black liquid solids are then burnt in a boiler. After the black liquor is fired the products of the recovery boiler are the steam, which is used throughout the mill, and the smelt, which is mixed with burnt lime to be processed in the causticizing area.

4.1.8 Recausticizing

The aim of this department is to maximize the recovery of the white liquor (NaOH and Na_2S). The chemical smelt that flows from the furnace through smelt spouts includes sodium sulphite (Na_2S), sodium carbonate (Na_2CO_3), and sodium sulfate (Na_2SO_4). The smelt is sent to a dissolving tank where it is dissolved in water to produce green liquor.

The median steam consumption in the recausticizing step is 0.44 GJ/odt (CIPEC, 2008). The average water consumption is 1.3 m^3/adt (Chandra, 1997) . The average amount of effluent produced is 1.4 m^3/adt (Turner et al., 2001).

4.2 Definitions and reasons for washing

Washing is an operation used in all kinds of pulp production processes; this unit operation is described as a solid-liquid extraction. Part of the motive for washing in the Kraft process is that the separation of spent cooking liquors and pulp has a large economic impact on the recovery system and the energy situation of the chemical pulp mill. (Miliander, 2009b)

Washing during Kraft pulping can be divided into two separate areas, each with its own distinct features, namely brown stock washing and washing in bleaching and, in some cases in the pulping department where a continuous digester is used (Krotscheck, 2008).

In brown stock washing, pulp and dissolved inorganic chemical substances are separated from the pulp. The main purpose of washing in this area is to remove the residual liquor that contaminates the pulp, prior to the next stages of the process. The second major purpose is to recover the maximum amount of dissolved substances, such as the organic material in the black liquor that is used as fuel in the recovery boiler and inorganic substances for the regeneration of the white liquor for the cooking, using a minimum amount of water (Pacheco et al., 2006)

An efficient washing stage enhances the recovery of spent chemicals, and decreases the consumption of reagents in the subsequent bleaching; essentially reducing the effluent load from the plant (Sillanpää, 2005).

The objective of washing in bleaching is to remove both dissolved organic and inorganic material, which will disturb the subsequent bleaching stage and increase the consumption of bleaching agents. As the optimum chemical conditions in subsequent bleaching stages vary, one crucial purpose of washing is to make the conditions more suitable for the next bleaching stage. This may include the modification of the pH, the temperature, and the content of metal in the pulp. In previous years, environmental concerns have become more important regarding pulp and paper production; pulp washing is becoming recognized as a critical step.

To produce fine papers and due to the possibility of integrated biorefinery Kraft mills, the lignin has to be either washed or bleached out and washer suppliers have been trying to reduce chemical consumption and energy consumption, also reducing the water used and organic material contained, such as chemical oxygen demand (COD), and biochemical organic demand (BOD) in the effluent (Orzechowska, 2006).

The efficiency of the brown stock washing operation is generally determined by measuring the residual soda loss in the washed pulp. Soda losses are typically expressed as pounds of saltcake (Na_2SO_4) per ton of pulp production.

4.2.1 Washing performance indicators

To understand better the **Figure 4-3**, the parameters L and V are described for each stream. By liquor means the amount of water and dissolved solids. Where the L and V are defined as:

$L_o \ = unwashed\ pulp\ stream$

$L_1 \ = washed\ pulp\ stream$

$V_2 \ \ = washed\ liqour\ stream$

$V_1 \ \ = filtrate\ \ stream$

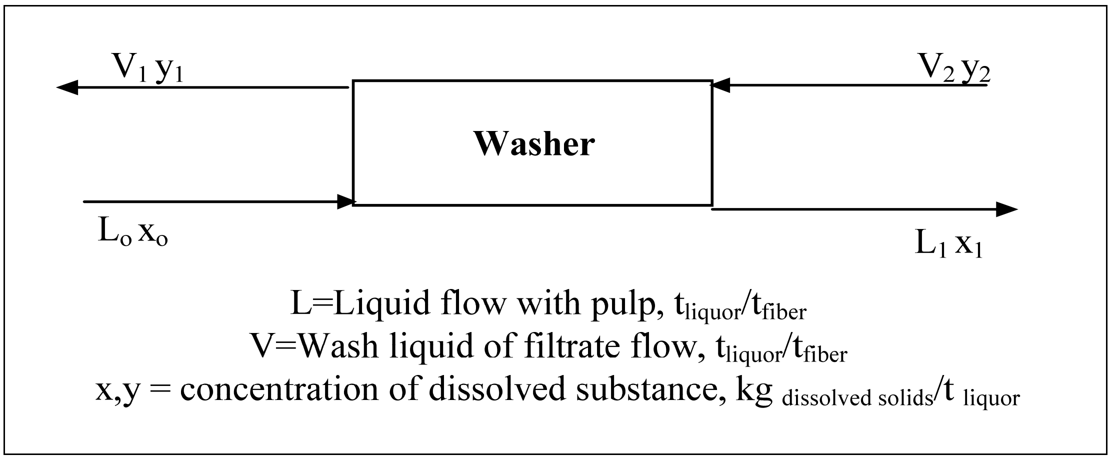

Figure 4-3: Basic schematic of the washing model

The parameters used to describe the performance of pulp can be divided into three categories, with parameters to describe:

- The amount of wash liquor used;
- The amount of solute removed;
- The efficiency of pulp washers operating under standardized inlet and discharge consistencies.

Amount of wash liquor used

The first category relates to the amount of water used in the washer and this category has three important parameters.

Dilution Factor, DF

The dilution factor is a measurement of the wash water applied in excess of that required for total displacement, expressed as mass of water per mass of oven dry pulp. Generally, a higher dilution provides better washing; it is also a direct measure of the water being added to the liquor system. Therefore, the washing benefit should be balanced against the higher evaporation load.(Smook, 1994). It can also be seen to represent the net amount of water being added during washing, and thus the evaporation load attributable to washing.

In order to understand the dilution factor it should be compared with what could be achieved on drum washers in series. With 3 washers in series a DF of 3 m^3 per ton of pulp was quite normal and 4 washers in series required 2.5 m^3 per ton of pulp. If the difference in DF is 1 m^3 per ton of pulp when comparing two different washing plants, it corresponds to another 1000 m^3 to evaporate per day at a production of 1000 ton per day. (Ek et al., 2009)

$$DF=V_2-L_1 \quad (1)$$

The description of this equation is:

$$DF=\frac{\text{ton of wash liquor entering- ton of liquor leaving the washer}}{\text{O.D. ton washed pulp}} \quad (2)$$

Wash liquor ratio, R

This parameter is defined with reference to the liquor leaving with the pulp. It is the ratio of the shower liquor flow divided by the liquor in the washed pulp stream. The consistency of the washed pulp must be known to relate R to DF. For displacement washing, R=1 implies that the liquor in the pulp pad was displaced by an equal amount of wash liquor.

$$R=\frac{\text{wash liquor entering}}{\text{liquor leaving with washed pulp}}=\frac{V_2}{L_1} \quad (3)$$

Weight liquor ratio, W

This parameter relates the filtrate flow rate to the liquor entering the washers with the pulp stream. When there is no change in consistency through the washer, R and W are approximately equal, provided the changes in liquor densities are small.

$$W=\frac{\text{filtrate liquor leaving}}{\text{liquor entering with unwashed pulp}}=\frac{V_1}{L_0} \quad (4)$$

Amount of solute removed,

There are two common ratios used to describe the solute removed from the pulp during washing, which are: the wash yield Y and the displacement ratio DR.

Wash yield, Y

This equation represents the percentage of solids removed in the pulp that has been washed.

$$Y=\frac{\text{dissolved solids removed}}{\text{dissolved solids entering}}=1-\frac{L_1X_1}{L_oX_o}=\frac{V_1Y_1}{L_oX_o} \quad (5)$$

Displacement Ratio, DR

The parameter used to describe the efficiency of displacement is the displacement ratio (DR). In the **Figure 4-3** where Y and X represent the concentration of solute in the different positions under consideration, Y and X can be either the chemical oxygen demand (COD) , dissolved solids (Ds) or the concentration of salt cake in the liquid phase. The definition of DR is as follows:

$$\mathrm{DR} = \frac{\text{Reduction of dissolved solids}}{\text{maximal reduction of dissolved solids possible}} = \frac{X_o - X_1}{X_o - Y_2} \quad (6)$$

Norden Efficiency Factor, E

The Norden efficiency factor is defined as the number of ideal stages in a countercurrent cascade with constant liquor and filtrate flow rates. The Norden efficiency factor, (E), is the most practical form for specifying washing efficiency. Also the most widely used efficiency parameter in computer aided mass and energy balancing. In order for this parameter to be applied, the system has to have the same feed and outlet consistencies.

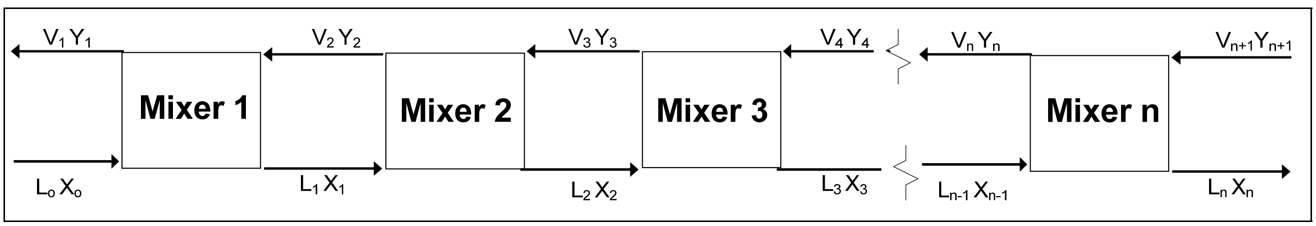

Figure 4-4: Washing system for n countercurrent mixing stages.

The ideal mixing stages are defined as vessels wherein the incoming streams are perfectly mixed and the effluent streams are in equilibrium. For example, in the mixer 1, the pulp stream L_o is perfectly mixed with the wash liquor stream V_2 and the liquor concentration in the departing streams are the same, i.e. Y1=X1. This occurs in all mixers.

The total mass balance of a washing system is given by:

$$L_o + V_{n+1} = V_1 + L_n \quad (7)$$

The total balance for the solids is done by:

$$L_o X_o + V_{n+1} Y_{n+1} = V_1 Y_1 + L_n X_n \quad (8)$$

Isolating Y_{n+1} from the equation 8 can be obtained:

$$Y_{n+1} = \frac{L_n X_n}{V_{n+1}} + \frac{(V_1 Y_1 - L_o X_o)}{V_{n+1}} \quad (9)$$

Supposing that there is an equilibrium in each stage, the equilibrium curve will be y =x. If the mass flows are constants in a process (L/V) = constant, la operational curve will be a straight line. The number of ideal stages can be determined in an algebraic way.

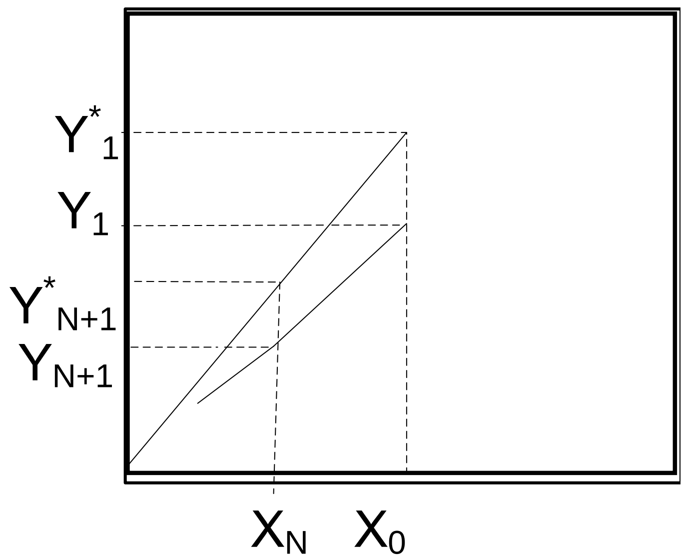

Figure 4-5.Relation hypothetical between y and x.

The operational curve for an equation,

$$Y_{n+1} = \frac{L}{V} X_n + \frac{(V_1 Y_1 - L_o X_o)}{V} \quad (10)$$

For the ideal stages $X_n = Y_n$

$$Y_{n+1} = \frac{L}{V} Y_n + Y_1 - \frac{L}{V} X_o \quad (11)$$

This is $X_o = Y_1^*$,

$$Y_{N+1} = \frac{L}{V} Y_N + Y_1 - \frac{L}{V} Y_1^* \quad (12)$$

For the first stage can be obtained,

$$Y_2 = \left(\frac{L}{V} + 1\right) Y_1 - \frac{L}{V} Y_1^* \quad (13)$$

For the second stage,

$$Y_3 = \frac{L}{V}\left(\left(\frac{L}{V}+1\right)Y_1 - \frac{L}{V}Y_1^*\right) + Y_1 - \frac{L}{V}Y_1^* \; (14)$$

Arranging,

$$Y_3 = \left(1+\frac{L}{V}+\frac{L^2}{V^2}\right)Y_1 - \left(\frac{L}{V}+\frac{L^2}{V^2}\right)Y_1^* \; (15)$$

For the stage number n,

$$Y_{N+1} = \left(1+\frac{L}{V}+\cdots+\frac{L^N}{V^N}\right) Y_1 + \left(\frac{L}{V}+\cdots+\frac{L^N}{V^N}\right)Y_1^* \; (16)$$

Simplifying,

$$Y_{N+1} = \frac{\left(1-\left(\frac{L}{V}\right)^{N+1}\right)}{1-\left(\frac{L}{V}\right)}Y_1 - \frac{L\left(1-\left(\frac{L}{V}\right)^{N}\right)}{V\left(1-\left(\frac{L}{V}\right)\right)}Y_1^* \; (17)$$

Expressed as,

$$\left(\frac{L}{V}\right)^{n+1}(y_1 - y_1^*) = \left(\frac{L}{V}\right)(y_{n+1} - y_1^*) + (y_1 - y_{n+1}) \; (18)$$

Afterwards the operational curve can be deducted.

$$(y_{n+1} - y_1) = \left(\frac{L}{V}\right)(x_n - x_o) = \left(\frac{L}{V}\right)(y_{n+1}^* - y_1^*) \; (19)$$

Combining the last two equations,

$$\left(\frac{L}{V}\right)^{n}(y_1 - y_1^*) = (y_{n+1} - y_{n+1}^*) \; (20)$$

Resulting,

$$n = \left(\frac{Log\,\frac{(y_{n+1} - y_{n+1}^*)}{(y_1 - y_1^*)}}{Log\,\frac{L}{V}}\right) \; (21)$$

Like $y_{n+1}^* = x_n$ and $y_1^* = x_0$

$$n = \left(\frac{Log \frac{(y_{n+1} - x_n)}{(y_1 - x_0)}}{Log \frac{L}{V}} \right) (22)$$

For the case of (L/V)=1 it can be obtained n using the equation 22.

$$n = \frac{(y_{n+1} - x_n)}{(y_1 - x_0)} (23)$$

In practice L is not constant along the washing operation. Norden proposed a modification to the formula assuming that the first stage of washing is not constant or ideal.

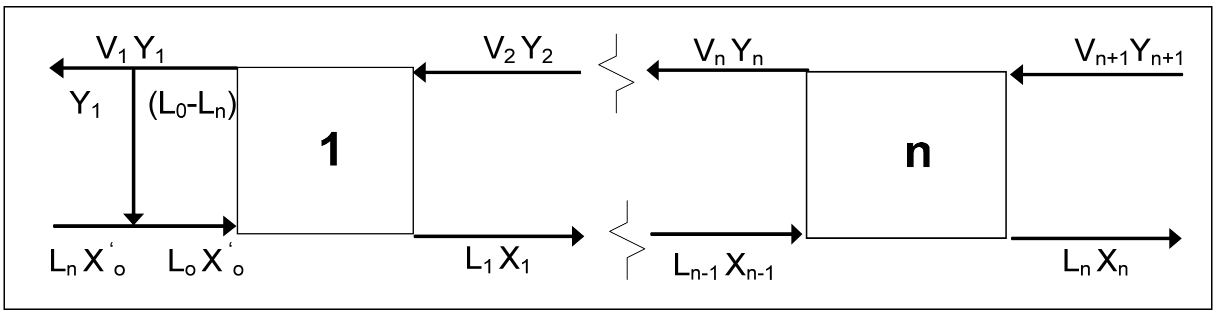

Figure 4-6: Washing system for a system where the first system is not in equilibrium

Using the **Figure 4-6** the Norden equation will be:

$$E = \left(\frac{Log \frac{(X'_0 - Y_1)}{(X_n - Y_{n+1})}}{Log \frac{V_{n+1}}{L_n}} \right) \quad (24)$$

X'_0 can be found performing a mass balance in the first stage,

$$L_n X'_0 + (L_0 - L_n) Y_1 = L_0 X_0 \quad (25)$$

To find the expression for X'_0

$$X'_0 = \frac{L_0}{L_n} (X_0 - Y_1) - Y_1 \ (26)$$

$$E = \left(\frac{Log \frac{L_0 \ (X_0 - Y_1)}{L_n (X_n - Y_{n+1})}}{Log \frac{V_{n+1}}{L_n}} \right) (27)$$

The value of the E factor depends on different variables, such as the type of equipment, the temperature, the mode of operation of the equipment, the diffusion and sorption, the type of pulp and the quality of shower. However, it is not possible to compare the efficiencies of two washing systems with different inlet and outlet consistencies.

Standardized parameters

There are two efficiency parameters, which may be used to compare washers operating at different inlet and outlet consistencies.

Modified Norden Efficiency Factor, E_{st}

Since the inlet and discharge consistencies should be the same, the Norden efficiency factor, (E), cannot be used when comparing different inlet and outlet consistencies. In response, the Modified Norden Efficiency factor, (E_{st}) was developed, which corrects for systems with different inlet and discharge consistencies. It is used as a way of correcting the inlet and outlet consistencies to 1% and 12 % respectively, which is useful when making comparisons between washers of different designs and operating ranges..

$$E_{st}=\frac{\log\frac{L_o}{L_1}\left(\frac{X_o-Y_1}{Y_1-Y_2}\right)}{\log\left(1+\frac{DF}{L_{st}}\right)} \quad (28)$$

Equivalent displacement ratio, (EDR)

The equivalent displacement ratio (EDR), like E_{st} is a performance parameter, which is independent of the inlet and discharge consistencies. It has been established as a mathematical tool for comparing washing equipment of different feed and discharge consistencies (Luthi, 1982). It expresses the performance of a washer in terms of a hypothetical washer operating at 1% inlet consistency and 12% discharge consistency.

EDR is calculated using the following equation:

$$(1-\mathrm{EDR})=(1-\mathrm{DR})(\mathrm{DCF})(\mathrm{ICF}) \quad (29)$$

Where:

DCF= Discharge correction factor $=\frac{100-C_d}{7.33*C_d}$ (30)

C_d= discharge consistency

ICF=Inlet correction factor

For dilution and thickening washers with no displacement washing,

$$\mathrm{ICF}=\frac{99}{\left\{99+\mathrm{DF}+\left(\frac{100-\mathrm{Cd}}{\mathrm{Cd}}\right)\right\}} \quad (31)$$

The equivalent displacement ratio, (EDR) and modified Norden Factor (E_{st}) are useful tools to compare the performance of washers or washing systems.

An advantage of the modified Norden Factor (E_{st}) is that this parameter can be easily calculated in terms of an equivalent number of theoretical stages for one washer and for a washing system it can be calculated by summing the individual E_{st}'s.

EDR is a simpler concept to understand and identify physically, as it relates directly to the fraction of solute removed.

4.2.2 Types of washing processes

The washing operation is based on five basic processes: dilution, mixing, dewatering, diffusion, and displacement. All the washers apply all or some of these processes in their washing arrangement.

The simplest method of washing occurs when the pulp is diluted with wash liquor, mixed and then pressed or filtered to take out the suspension. Another of the basic methods is when the shower flow replaces the liquor from the pulp mat, which is called displacement.

Pulp washing is accomplished either with clean water or wash liquor (water with dissolved solids). The general term "wash liquor" will be used to describe both clean water and washing liquid. There are different possible ways to bring the pulp and washing medium into contact.

4.2.3 Washing by dilution and extraction

In dilution and extraction washing, the pulp suspension is diluted and thoroughly mixed with weaker wash liquor or clean water as can be seen in **Figure 4-7**, stage one, and then thickened by filtering, either assisted by a pressure difference across the pulp mat or by applying pressure, as shown in **Figure 4-7** stage two. Dilution and extraction will not remove all impurities unless it is repeated several times. In theory, an infinite number of dilution and extraction washing stages is needed to bring the concentrations in the pulp discharge to their levels in the wash liquor (Krotscheck, 2008).

The efficiency of this operation is generally low, and depends primarily on the consistencies to which the pulp is diluted and thickened. It also depends on the extent to which solute is absorbed on the fibers and the time required for the solute to diffuse out of the fibers (Krotscheck, 2008).

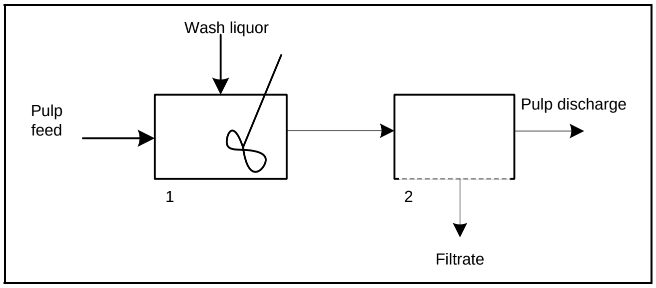

Figure 4-7 Dilution and extraction principle based on Gullichsen & Fogelholm (2000).

4.2.4 Washing by displacement

Displacement washing is based on the concept of replacing the liquor in the pulp mat with wash liquor rather than mixing these two liquors. Appropriate displacement washing is of primary importance in obtaining good washing efficiencies with all types of washing equipment.

The principle of displacement washing is illustrated schematically in **Figure 4-8**. A volume of wash liquor is added to the pulp feed in the first stage, in a way that the wash liquor pushes out the liquor entering with the pulp feed as filtrate, as in stage two. In the third stage, the wash liquor occupies all the space originally held by the liquor in the pulp feed. Ideally, the displacements of the liquid phase permit the extraction of all the dissolved solids. However, in practice this is far from possible due to the effect of the two liquid phases mixing and the diffusion and absorption of impurities in the fibers (Morimanno, 1989).

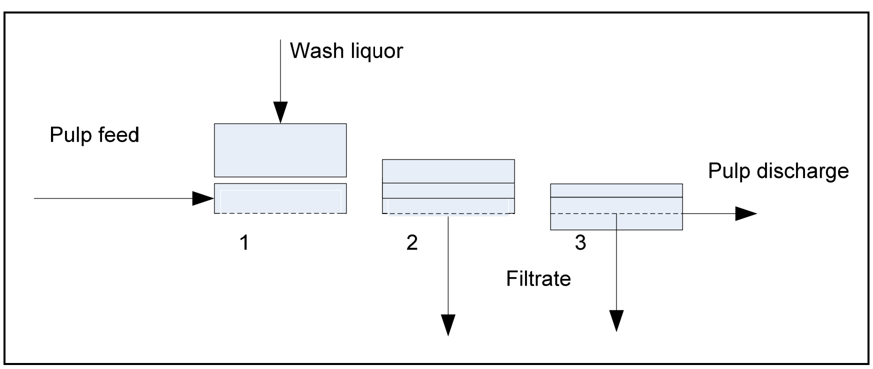

Figure 4-8: Displacement washing based on Krotscheck (2008)

In displacement washing, the liquor in the pulp mat is displaced with wash liquor. Minimizing the mixing in the interface between the wash liquor and the liquor in the pulp is recommended. If no mixing occurred, it would be possible to remove all the solute impurities from the pulp, but in practice it cannot be achieved, because of diffusion from the pulp fibers. (Crotogino et al., 1986).

4.2.5 Compressive dewatering

Another way of reducing the unwanted impurities that are carried out with the pulp is the removal of liquor by applying pressure. In **Figure 4-9** this principle is illustrated, where the pulp enters the washer (stage one), where an external force is applied to displace the shower liquor (stage two) and the pressure rises, increasing the liquor removed from the pulp (stage three).

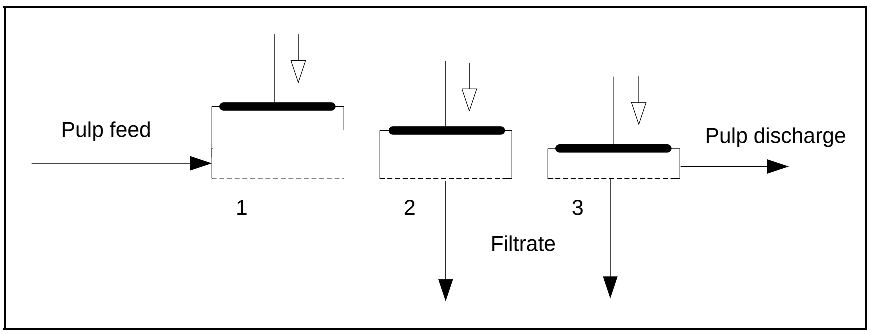

Figure 4-9: The principles of compressive dewatering based on Krotscheck (2008)

Contrary to displacement washing, which is based on a change in liquor concentration, compressive dewatering decreases the amount of unwanted substances in the pulp discharged in the washer by reducing the liquor in the pulp stream.

4.2.6 Multistage washing

Most of the time, one washing stage alone is insufficient to carry out the required washing. To overcome this, many pulp washing stages are used. In these cases, multi-stage configurations either through single washers in a series or a single multi-stage washer can be used.

The quantity of stages depends principally on the required washing efficiency. In a multi-stage system, the maximum solute removal will be achieved if the pulp is washed in each stage with clean water. This approach is called a cross-flow approach, which is depicted schematically in **Figure 4-10.**It requires large quantities of fresh water and, is, therefore, not acceptable in practice (Crotogino et al., 1986).

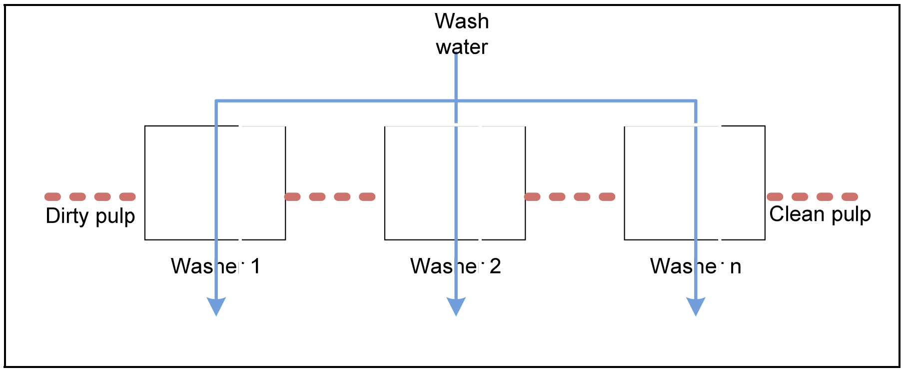

Figure 4-10: Cross-flow washing based on Crotogino (1986).

The common practice is to use a counter-current principle in multi-stage wash plants, where the wash medium flows counter-current to the pulp flow. The pulp in the final wash stage is washed with the cleanest available wash liquor before it leaves. The filtrate from the last stage becomes the wash liquor for the previous stage until it reaches the first washing stage, as depicted in **Figure 4-11**. The filtrate of the first washing stage, which contains the highest concentration of solids, is sent to the evaporation department.

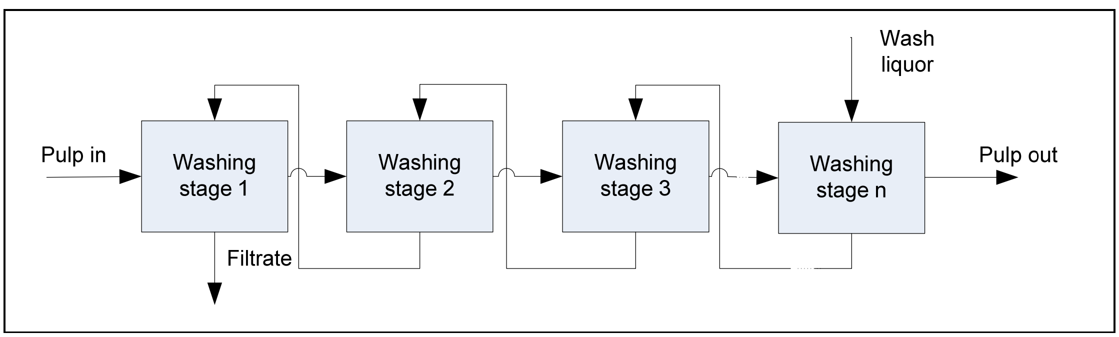

Figure 4-11: Counter-current washing stages based on Krotscheck (2008)

Besides the advantage of producing a limited amount of filtrate at high concentration, countercurrent washing also promotes energy efficiency as the reduced amount of filtrate limits the energy leaving the system. As mentioned previously, less energy will be required in subsequent parts of the evaporation process.

The efficiency of multi-stage washing depends on the way the pulp is transported between stages. If an intermediate mixing between stages exists, it will reduce the washing efficiency compared to when no mixing takes place, as presented in **:** .

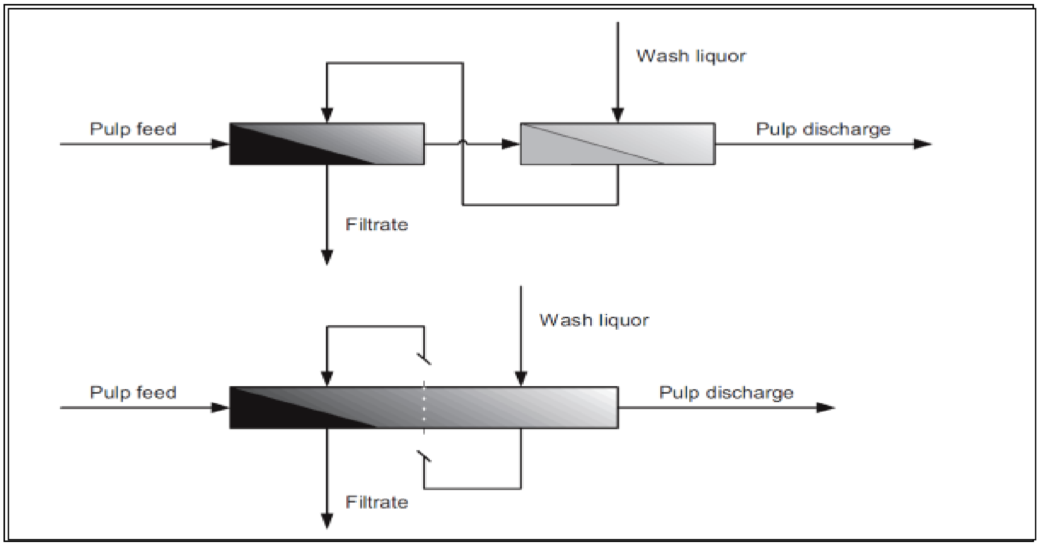

Figure 4-12: Two-stage countercurrent washing with and without intermediate mixing based on Krotscheck (2008)

4.2.7 Fractional Washing

Fractional washing is an extended technique of countercurrent washing, where typically the filtrate is divided into two parts with counter current circulation. It is applied in drum displacer washers, due to over 75% of the drum area being available for washing. Fractional washing has different properties that can be used to improve total system efficiency in brown stock washing and in the recirculation of bleach plant filtrates (Tervola et al., 1993).

In the **Figure 4-13**, four ways are shown to perform two washing stages, with calculated washing efficiencies and losses shown for each case. In the example number one pulp is mixed in a pump between two washing stages with only one filtrate stream. In the second example no mixing between washing stages is showed, which is the most common washing configuration in pulp mills. The third and fourth examples both demonstrate fractionation, with the difference being that mixing between stages decreases the washing efficiency. The fourth example shows a patented drum displacer (DD) principle.

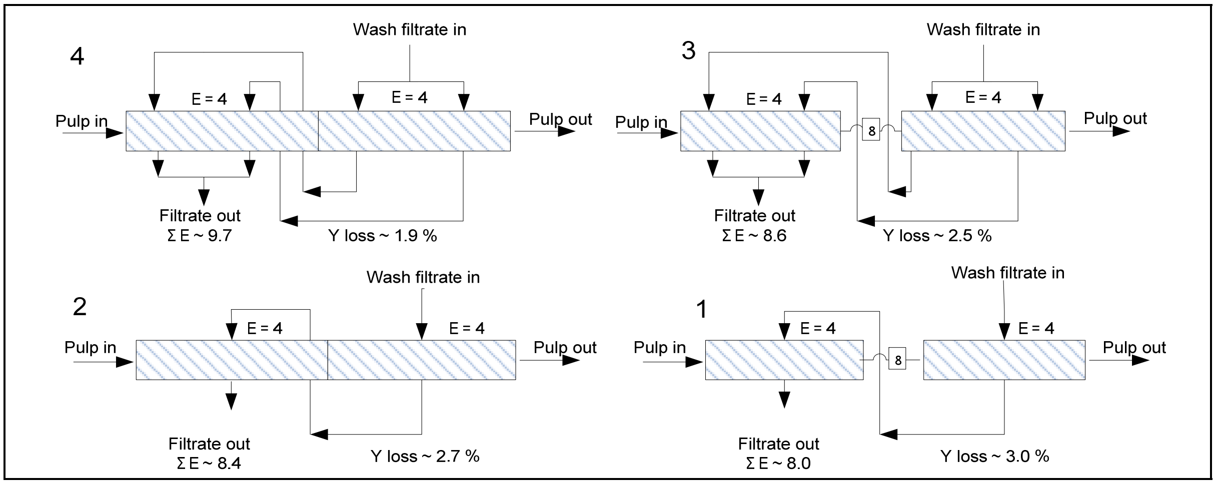

Figure 4-13: Methods of two-stage washing (Gullichsen & Fogelholm, 2000)

4.3 Practical utilization

There is a large and growing variety of commercial pulp washing equipment available on the market today. Brown stock washing is a key unit operation in the production of Kraft pulp, with operating parameters that affect the efficiencies of bleaching, evaporation, and the recovery cycle. The most common type of washer in brown stock washing and bleach plants is the rotary vacuum washer (Crotogino et al., 1986), with other types of washers being the vacuum drum, pressure diffuser, diffuser, and chemical. Often, a combination of different types of washers is used to achieve higher washing performance in pulp and paper mills. (Turner, 2001).

The addition of a complete new washing stage is often not feasible due to high cost and space constraints. Reconfiguration of existing stages to employ filtrate segregation may provide incremental improvement in washing efficiency. (Antkowiak, 2000). Some new alternatives to the rotary vacuum drum washer include the Drum Displacer TM, Pressure Diffuser, Chemi-washer, Compaction Baffle Filter and Wash Press (Turner, 2001).

4.4 Type of washers

As mentioned before the most common and the first type of continuous washer to be developed was rotary drum washers. For many decades, the standard method of washing was to employ a series of rotary vacuum washers operating in a counter-current flow configuration.

The most common washers are: the washing zone in continuous digesters, drum washers (rotary vacuum drum, drum displacers and compaction baffle filter), wash press, diffuser (atmospheric and pressure) and chemi-washers.

Every type of washer must provide the drainage area necessary to perform the initial dewatering, displacement, and final thickening of the pulp. Time also plays a very important part in the diffusion process. In this respect, every washer shows wide differences.

Washing equipment with both inlet and outlet at medium consistency does not require intermediate dilution between stages. Such systems are associated with relatively small flow rates of wash medium and extracted filtrate, thus reducing pumping requirements and the corresponding energy consumption. It also applies for equipment with medium consistency inlets and high consistency discharges and has the advantage that washing can be achieved with a smaller amount of wash liquor.

The E-factor is frequently given for different types of equipment, preferably if the units are working at constant consistency, which gives a high E-factor.

4.4.1 Washing zone in continuous digesters

Nowadays, most continuous cooking systems use a washing stage before the digester discharge.

The digesters are split into different zones: impregnation, cooking, and washing. At the end of the washing, the temperature is lowered to (100°C), allowing the heat recovery and the discharge of the pulp.

The efficiency of Hi-Heat washing in continuous digesters depends largely on the design of the cooking system. Due to the elevated temperature and long duration, Hi-Heat washing can reach E factors up to 9.

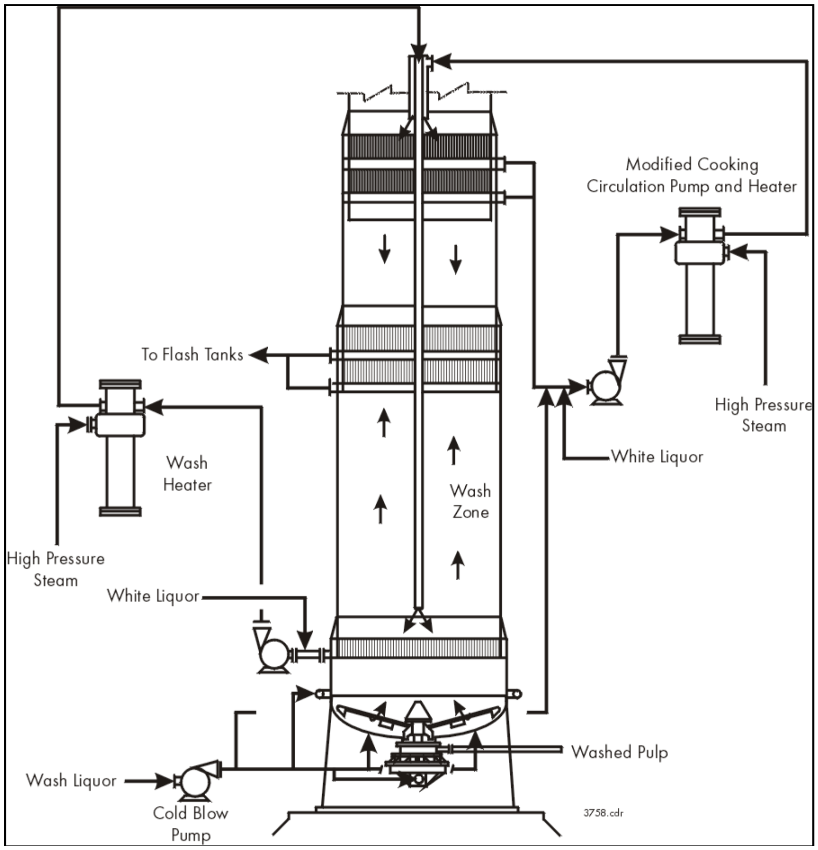

Figure 4-14: Washing zone in a continuous digester used by permission of Andritz.(Poulin, 2011)

4.4.2 Drum displacers

The most common and the first continuously operated washing systems were based on using a series of single-stage drum washers. There are several types of drum washers categorized in two groups, those that operate with a lower than atmospheric internal pressure (vacuum washers) and those with a pressure higher than atmospheric outside the drum (pressure washers) (Gullichsen & Fogelholm, 2000). Conventional drum washers can be categorized into vacuum washers and pressure washers.

Convectional Rotary Vacuum Drum, (RVD)

The washing efficiency of a filter depends on both dilution and thickening of the pulp suspension and displacement liquid being added through the nozzle to the pulp pad. Deckers are a type of washer that are used in the last stage of brown stock washing; originally without showers, current practice is for showers to be included with a decker (Brouillette, 2010).

A typical inlet range of consistency is between 0.5 and 1.8% to feed to the washer vat. The DR value is in the range of 0.7 for a drum filter, the value depends on the amount of wash liquor. The range of typical EDR is 0.58 to 0.78 according to Tuner (2001).

Vacuum filters operate with a pressure slightly below atmospheric pressure on the filtrate side created by a fan or a vacuum pump. The pressure difference between the atmospheric pressure and the pressure inside the drum helps the flow of the filtrate and the buildup of the pulp mat.
The capacity of the filter depends primarily on the pressure difference that can be maintained over the pulp mat.

Two types of vacuum filters should be compared in this respect. The highest vacuum is achieved with a vacuum pump and an external drop leg to a filtrate tank. The vacuum is then limited by the steam pressure of the water as the actual temperature and for that reason the drop leg has to have a length corresponding to the pressure drop. The temperature of the filtrates should not exceed 80°C to 85°C because it will be evaporated due to the vacuum in the equipment.

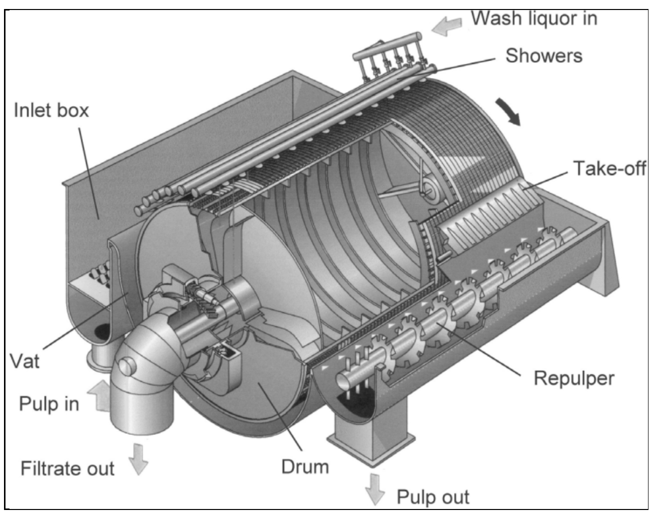

Figure 4-15: Rotary Vacuum Drum (Brännvall, 2009)

Pressure drum

Pressure washing is similar to vacuum drum washing, but differs by spraying water under pressure through the pulp mat as the drum rotates. In this type of washer, the compaction baffle filter is categorized. This type of washer is extremely efficient and probably the most popular choice for new washing equipment, because due to operating pressure, the high temperatures are not a problem and the filtration tank does not need to be placed below the washer, requiring much less building space than conventional vacuum or pressure washers. The main disadvantage is that they are difficult to control (A. Orzechowska, 2006)

The compaction baffle filter (CBF) is a relatively compact pressurized washer that requires much less building space than conventional vacuum or pressure washers. Typical outlet consistencies are from 14% to 18% and typical EDR is in the range of 0.80 to 0.85 according to Turner (2001)

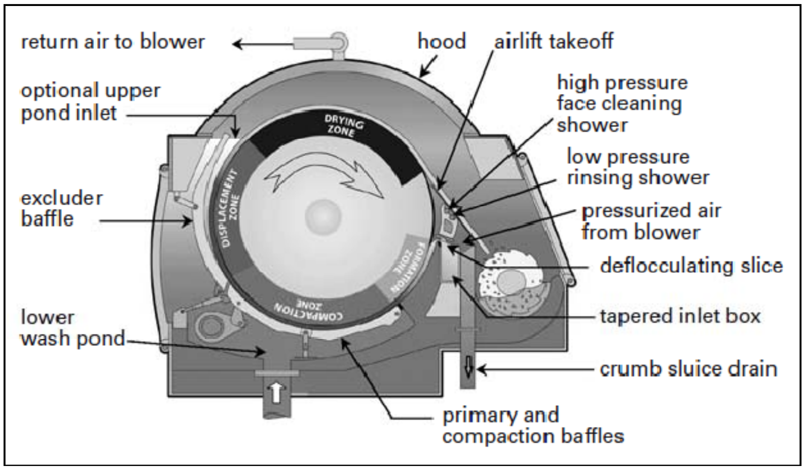

Figure 4-16: Compaction Baffle Filter (Brännvall, 2009)

Wash Presses

Metso Twin rolls are designed to handle either low consistencies (3% - 5%) or medium consistencies (6% - 10%). As the pulp stream enters the press, a mat is formed in the dewatering zone, where the pulp consistency is raised to 8% - 12% as the pulp moves between the rolls. All stages, including dilution, rethickening, displacement, and pressing to 30% -35 %, are included in sequence in one single unit. For efficient washing, wash presses rely on high discharge consistency, and this means they are not as good in areas where the liquor has higher viscosity, such as the beginning of brown stock washing. They are most used after oxygen delignification stages or even in bleach plants. A normal range of DR for a wash press is 0.5 and 0.7 and with dilution and thickening, this gives a total washing efficiency of over 90% (Gullichsen & Fogelholm, 2000). Wash press factors are around one, and the E_{10} range between 3 and 5. The enclosed press allows high feed temperatures, minimizes foaming and allows the elimination of gases. The range of typical EDR is 0.83 to 0.92 according to Tuner (2001).

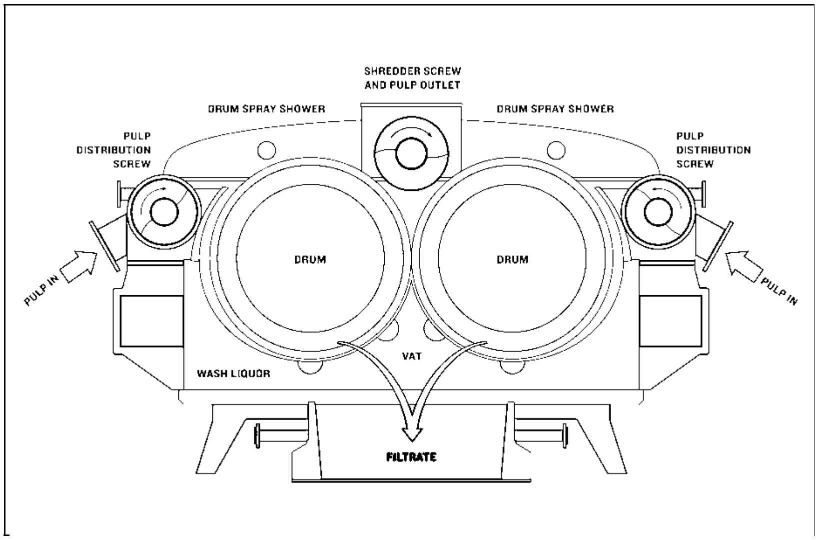

Figure 4-17: Twin Roll wash press used by permission of Metso, Finland. (Ramark, 2011)

Drum displacers, DD

One of the main characteristic of the drum displacer is that it can produce several filtrates with different properties. Those filtrates can be used in certain way that the filtrates can be sent to the evaporation department and the cleaner filtrates used as shower flow in the next washer.

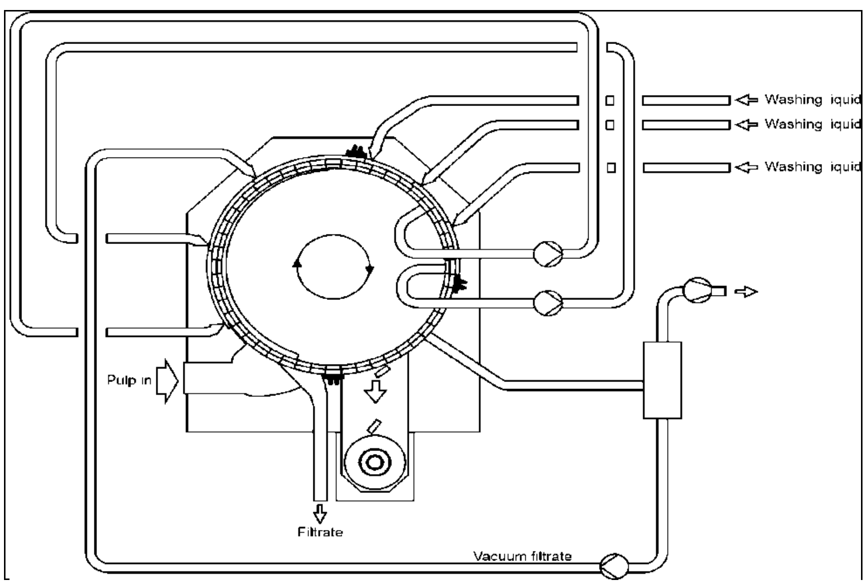

Figure 4-18: Drum displacer used used by permission of Metso, Finland. (Ramark, 2011)

4.4.3 Diffusion washing

Diffusion washing is a counter flow process that takes place in one or more stages. Pulp flow is upward and is carried on a perforated plate; water flow is downward through a series of baffles. This method offers a high degree of cleaning with low water use. Pressure diffusers are now the preferred washer technology for feed from a continuous digester. They can be considered almost as an extension of the digester wash zone higher temperatures are not a problem in this type of washer.

Washing efficiency is greatly improved at higher temperatures due to the greater diffusion rate of material from inside the fibers and the greater solubility of soaps. This type of washing is classified in two categories: atmospheric diffuser washer and pressure diffuser washer.

Atmospheric diffusers are not as popular now, mostly because of the high efficiency of pressure diffusers. In general, pressure diffusers are not a good option as the last washer of a line because of their relatively low discharge consistency (Orzechowska, 2006)

Atmospheric diffuser, (AD)

Typical features of an AD are efficient washing, low energy consumption and simple operation. The most common application of an AD is in the brown stock washing section after continuous cooking, where they reduce energy usage and maintenance expenses. Pulp is fed into the machine at digester blow consistency directly from the digester blow line. The AD is installed after an oxygen delignification stage with a wash press. The combination of the two different types of washers (displacement and press) results in good overall system performance where the benefits of each washer are added to the system.

This machine normally operates in the consistency range of 10% - 12% for entering and exiting pulp. In some cases when the diffuser is before a wash press, a dilution sequence can be incorporated with the exiting consistency of about 5%.

The principle behind the atmospheric diffuser is displacement. As the name indicates, it operates at atmospheric pressure. The washing efficiencies measured as E_{10} values are 3.4 - 4.0 for one stage diffuser and 6.5 -7.5 for two diffusers. The high washing efficiency is due to the high washing temperature, long retention time, good displacement, and air-free conditions.

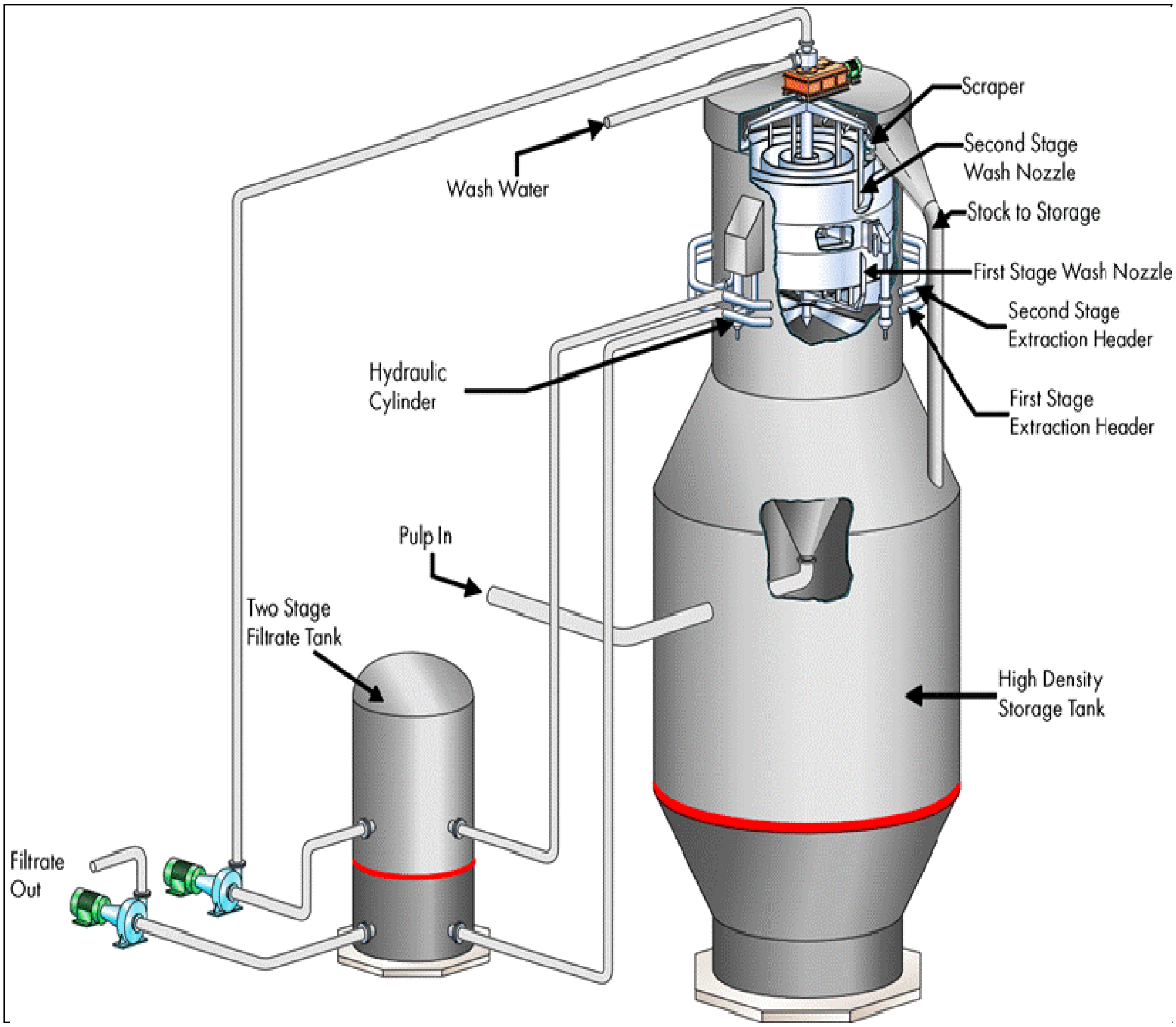

Figure 4-19:Atmospheric diffuser used by permission of Andritz (Poulin, 2011)

Pressure diffuser (PD)

Pressure diffuser systems require very little space for installation and are easily retrofitted into the blow line of an existing digester system. Pressure diffusers are a fully enclosed diffusion-type washer that operates under pressure. The washing efficiency is reached purely by displacement since the unit operates at constant consistency all the way from pulp inlet to the outlet. The displacement ratio is high because there is a homogeneous distribution of the pulp and wash liquor. The entrained air is avoided due to the equipment being sealed and pressurized and operating at high temperatures. The pulp flows vertically upward in one design (Ahlstrom Machinery now Andritz) and downward in another design (Kvaerner Pulping now Metso).

However, the fact that the pulp flows upward in the Andritz pressure diffuser has the advantage that if the pulp contains gas, the gas leaves the diffuser with the pulp without affecting the operation.

Pulp at medium consistency enters the top of the machine. The E_{10} value for Norden factor efficiency of the pressure diffuser is 5.0 – 5.5, with the high value due to good displacement, high temperature, air free washing and slow displacement. The range of typical EDR is 0.80 to 0.85 according to Tuner (2001). Energy consumption is less than 10 kWh/adt because no dilution and thickening during washing is necessary. When the pressure diffuser follows a continuous digester, a stock pump is also unnecessary. Maintenance is easy since the unit has only two moving parts and no wires (Gullichsen & Fogelholm, 2000).

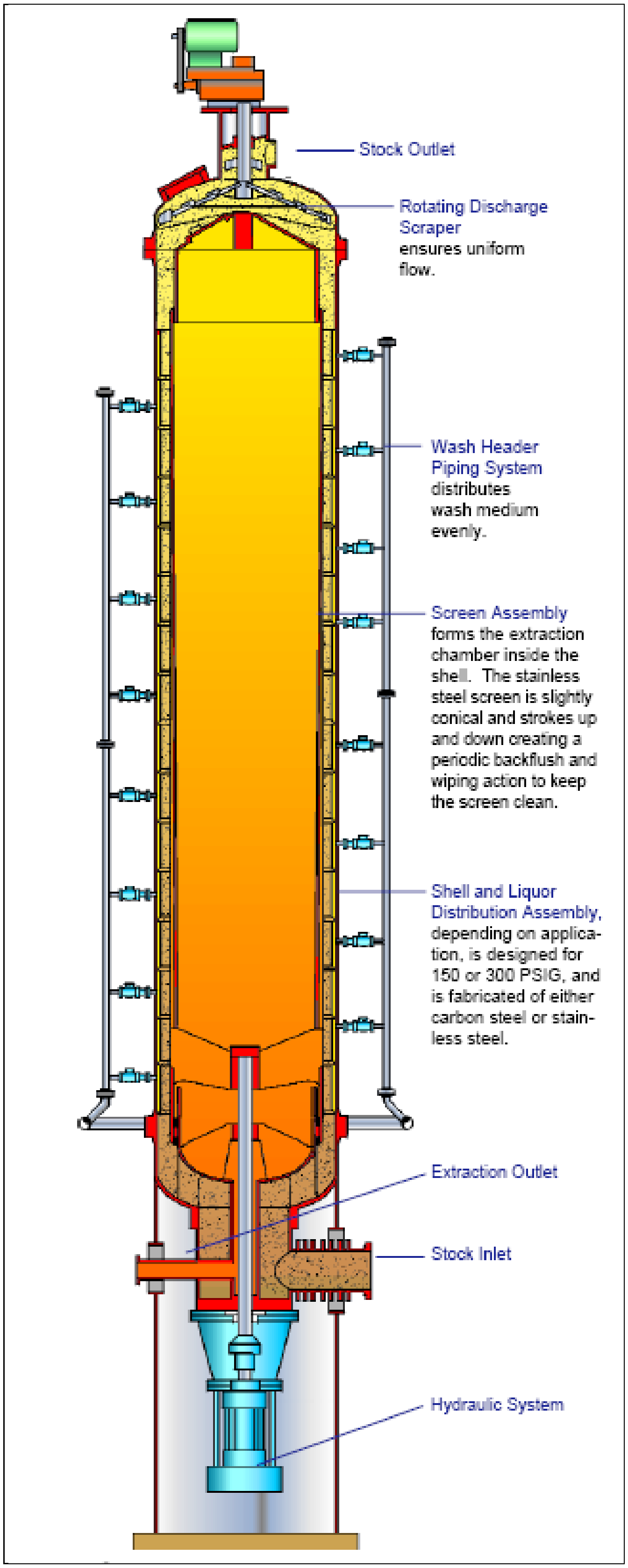

Figure 4-20: Pressure Diffuser schematic used by permission of Andritz (Poulin, 2011)

4.4.4 Belt washers

Belt washing is a counter flow process where pulp enters the washer area on a wire and washing takes place under a series of showers. Belt washing applications range from brown stock washing to post-oxygen washing to bleaching washing. The most common belt washer is the chemi-washer presented in **Figure 4-21**.

Pulp is fed to a consistency of 2.0 to 3.5% and distributed evenly on the moving wire. There is a zone from the head box to the first shower where the pulp is dewatered, then there are some suction boxes below the wire that collect the liquor, which is sent to the previous stage. The efficiency of this type of washer is optimized by controlling the vacuum profile in the suction boxes, the speed of the wire, the length of the dewatering zone and the distance between the headbox and the first shower. Typical outlet consistencies range from 10% - 14% and normal dilution factors are between 1 – 2 m^3/odt. The chemi-washer has up to seven washing stages; the belt is the most efficient of all the washing equipments. The E factor per stage is in the range of 2.0 and 2.5.

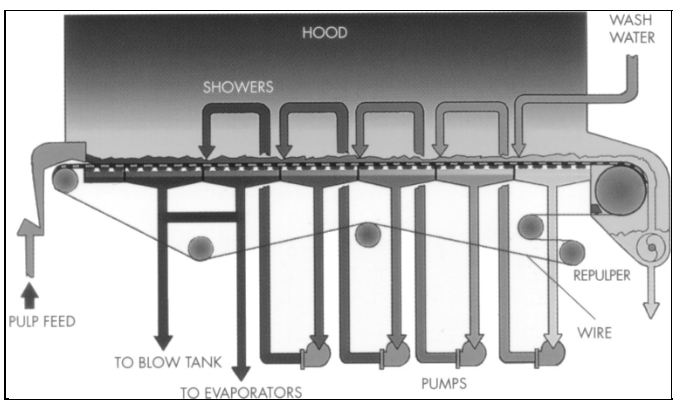

Figure 4-21:Chemi washer used by permission of Kadant (Tyler, 2011)

4.5 Variables affecting washing performance

In this section, a review of the parameters that affect the operation of washers will be presented. They include process conditions, such as the dilution factor, feed and discharge consistencies, pH, shower flow temperature, entrained air, drum velocity, tank level, production rate, pulp pad thickness and washer vacuum (Crotogino et al., 1986; Korhonen, 1979a). Most of these variables have been evaluated by Hakamaki & Kovasin (1985) for rotary vacuum drums.

There are several variables that affect the efficiency of the removal of soluble solids and sodium from Kraft pulp. Some of these variables are fixed in the washer design, and other are controlled during operation of the washer.

The operational washing variables can be divided into independent and interdependent variables. An independent variable can be changed without significantly affecting any other variable. An interdependent variable cannot be changed without affecting another variable (Korhonen, 1979b).

The independent variables include the amount of shower flow, shower flow temperature, entrained air, production rate variation, shower-flow distribution among the pipes. The interdependent variables are drum rotation speed, consistency, and drum vacuum. (Korhonen, 1979b). Optimization of the washing variables is important for efficient mill and washer operation.

4.5.1 Shower flow

The shower flow is represented by the dilution factor, it is defined as the difference in wash liquor of the shower flow and the liquor of the pulp stream, as it can be seen in equation (1).

When the dilution factor is negative, a fraction of the contaminated liquor remains with the pulp and stays in the pulp stream as carry over. When the dilution factor is a positive dilution factor, there exists a clear correlation of washing efficiency and dilution factor. Regardless of the arguable beneficial effect on washing efficiency, a high positive dilution factor can affect subsequent stream in the mill. In the case of brown stock, a high dilution factor means additional evaporation requirements, and in the case of bleaching, the increased filtrate flow places a challenge on the water treatment plant.

As a rule of thumb, drum and belt washers are typically operated at a dilution factor of 1-3 m^3/odt, and wash presses at 2-4 m^3/odt (Krotscheck, 2008).

4.5.2 Feed and discharge consistencies

The feed consistency has a major influence on the electrical energy consumption. A low feed consistency means that large volumes of filtrate are pumped to dilution pumps before the washers, and as a consequence, a lot more electricity is used to transport it.

4.5.3 pH

The pH in the pulp is a function of the preceding stage and the origin of the wash liquor. It is not common to adjust pH as a control parameter for washing; only in a few cases is controlling the pH beneficial and desirable. One process modification that can affect the pH is the brown stock acidification, the most common acid being CO_2. The function of acidification of the pulp is that the pulp will not swell as much at a reduced pH, which makes washing easier.

4.5.4 Wash water temperature

Wash water temperature affects washing efficiency appreciably. The temperature has an effect on the removal of the dissolved solids in the pulp; as the temperature rises, the efficiency increases. This relationship has been confirmed experimentally in drum washers, and for this reason, optimum wash water temperature is recommended to be the temperature at which the first-stage vat liquor temperature is a few degrees lower than its bubble point temperature at leg vacuum. In **Figure 4-22** the effect of the temperature on washer capacity can be seen, with increased temperature indicating improving washing efficiency.

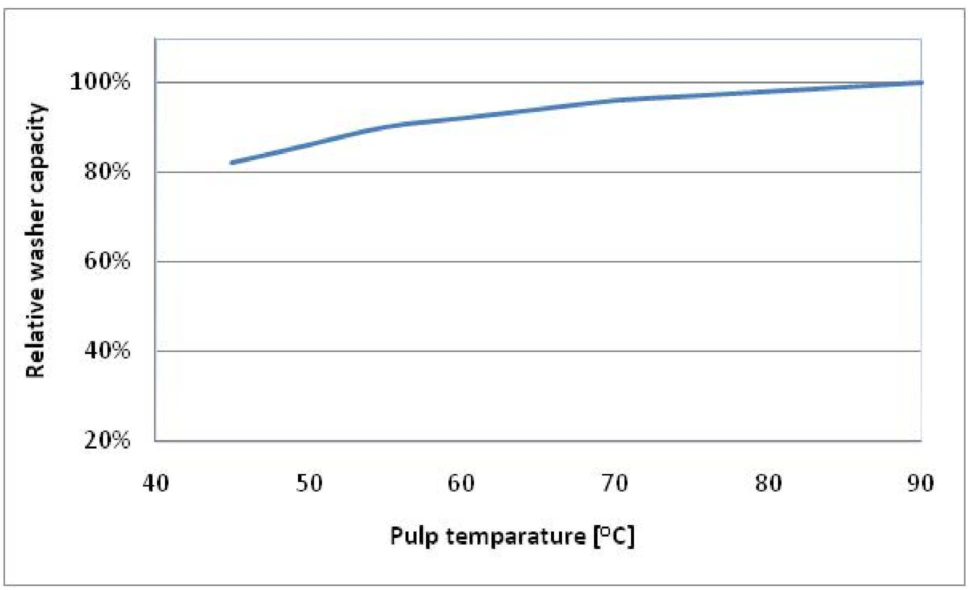

Figure 4-22: Temperature effect on washing based on Krotscheck (2008).

4.5.5 Entrained air

Brown stock defoamers reduce the foaming action by the use of surfactants, which help to reduce entrained air in the system. The amount of defoamer used depends on the defoamer quality, instrumentation, and flow control, but the most significant aspect is the operator manipulation. The efficiency of the defoamers depends on the black liquor composition, which is different for each mill. Regular supervision is suggested in order to keep defoamer consumption at an economical level (1.3 kg/ton of fiber)(Hakamaki & Kovasin, 1985). According to the correlation developed by Kovasin & Hamaki, the washing capacity is affected by the presence of air in the pulp feed, as described in **Figure 4-23**.

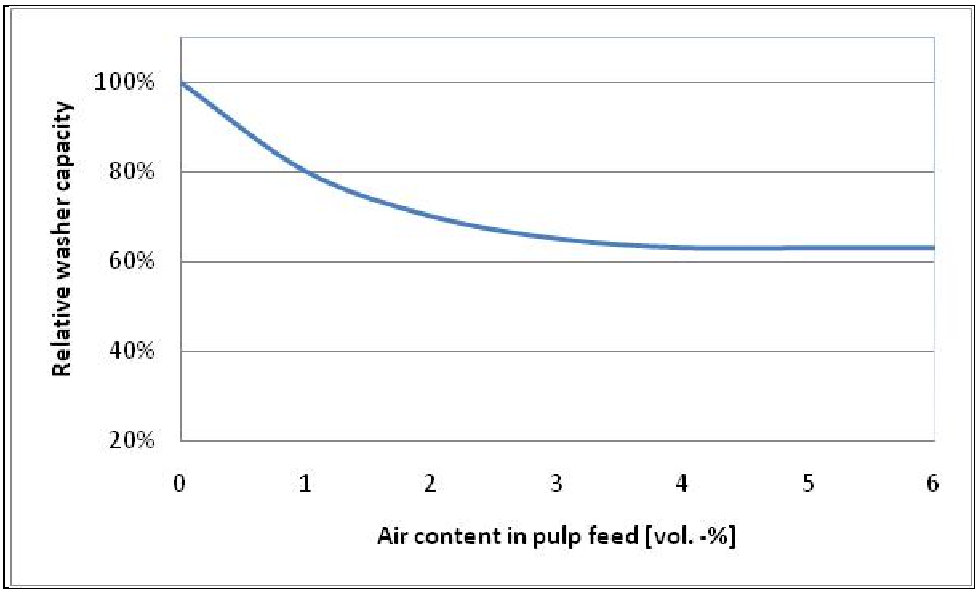

Figure 4-23: Effect of the air content in the pulp in the washer capacity based on Krotscheck (2008)

4.5.6 Drum rotation velocity

Drum speed affects sheet thickness and residence time on a vacuum drum. An optimum speed for sheet thickness exists, since a sheet that is either too thick or too thin results in poor washing. Optimum thickness depends on drum mechanical structure, drum surface area, and production rate.

In practice, it is often necessary only to emphasize the need to keep drum speed low, because operators tend to use higher speeds. According to Hakamaki & Kovasin, (1985) the best range of operation is between 2 and 3.5 revolutions per minute for a drum washer.

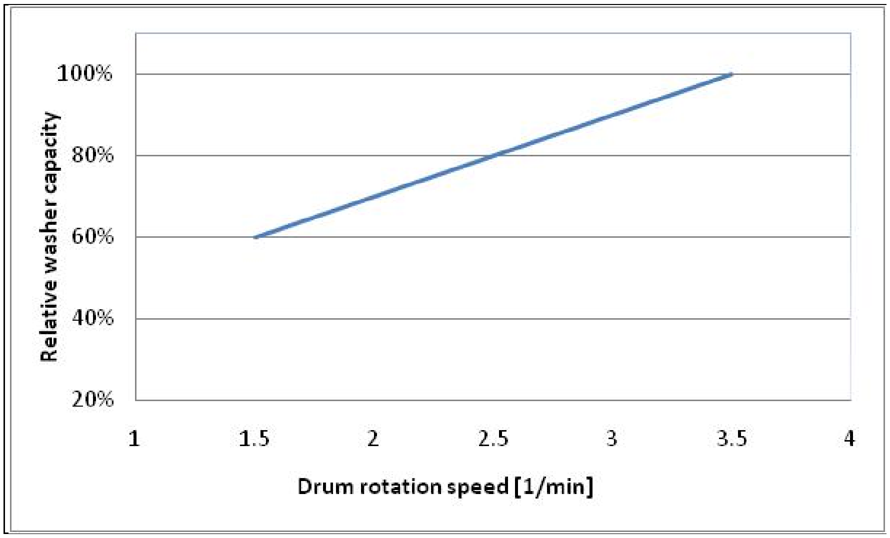

Figure 4-24: Effect of the drum rotation velocity on the washer capacity based on Krotscheck (2008)

4.5.7 Production rate

Many older mills have production rates that have increased steadily, but still use original washers that tend to be overloaded, which inevitably leads to poor washing efficiency. Typical washer loading factors are given in **Table 4-2**. However, modifications can be made to original washing equipment which can allow mills to run at increased production levels without sacrificing washer performance.

Table 4-2: Typical Washer Loading Factors (Turner et al., 2001)

Washer Type	Loading Factor [adt/day/m^2]
Vacuum Drum (old)	<7.5
Vacuum Drum (new)	<9.7
Wash Press	<27
Pressure washer (CBF)	< 21 -27

4.5.8 Pad thickness

According to Sillanpää (2005), the increasing thickness of the pad increases the washing efficiency.

4.5.9 Vacuum levels

Drum vacuum depends on dilution flow, height of the vacuum leg, vat level, production rate, drum speed, and wash water temperature. Vacuum is rarely adjusted and is set at its maximum possible value. Vacuum is reduced with an increase in vat consistency. The loss of vacuum is an indication of flashing or mechanical problems in vacuum head. Abnormal vacuum levels can be utilized to detect high filtrate liquor temperature and/or seal leakages.

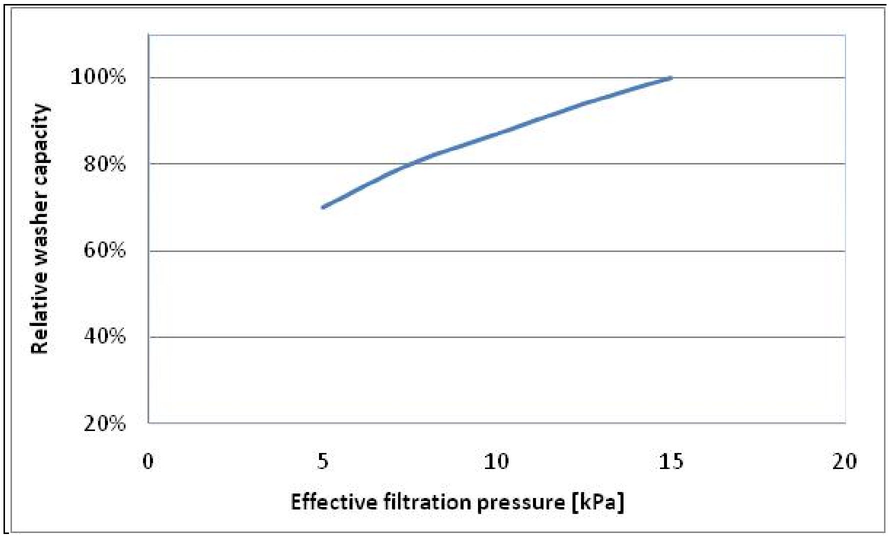

Figure 4-25: Effect of the vacuum on the washer capacity based on Krotscheck (2008)

4.6 Best Practices

The typical brown stock system consists of a series of three or four rotary vacuum drums, where water is used to wash the pulp and dissolve solids in the pulp.

Pulp washing can occur on presses, which have a washing efficiency of 70% - 85% and filters, which have a washing efficiency of around 65%. The press is a considerably better pulp washer than a filter, but has larger capital costs (Martin et al., 2000).

However, lower building costs and smaller filtrate tanks can compensate or even outweigh the higher capital cost requirements of press washing. Savings in steam and chemical consumption provide additional benefits. Therefore, a press-bleach plant may be a competitive alternative for a new pulp mill.

4.7 Typical values for performance parameters

Depending on the type of washer, there are some parameters that can be used to determine if the equipment is working within its optimum range. The parameters are Equivalent Displacement Ratio, (EDR), Modified Norden Efficiency factor (E_{st},) and the percentage of solids removed from the pulp.

In **Table 4-3**, the EDR can be found for different equipment items and used for comparison if the value that is calculated for the current operation conditions of the mill is inside the range or not.

The modified Norden Efficiency factor, E_{st} is a parameter that can be used only if the DF in the base case is 2.5; this in reality rarely occurs.

When the benchmarking is performed against typical values, this parameter supports the EDR principally due to the fact that there are no typical values for most of the equipment.

Also, the yield can be used to evaluate the dissolved solids removal in pulp, presented in the equation number (5). For this key performance indicator there is not a value for each equipment item, as understood in the literature the all the equipment should have a higher yield than the rotary vacuum drum because this equipment has the lowest efficiency.

Table 4-3: Typical washing performance indicators for the most typical equipments.

Equipment type	**EDR (12 % Discharge Cs)**	**Modified Norden Efficiency (10% Discharge Cs) DF= 2.5**
Digester wash zone	0.93(T. M. Poulin, 2005)	E_{10} 4 - 6 (Smook, 1994)
Pressure diffuser	0.80 - 0.85 (Turner, 2001)	E_{10} 5.0 - 5.5 T.M. Poulin, 2010)
Atmospheric diffuser 1-stage	0.76 - 0.90 (Turner, 2001)	E_{10} 3.4 - 4.0 T.M. Poulin, 2010)
Atmospheric diffuser 2-stage	0.92 - 0.96 (Turner, 2001)	E_{10} 6.5 - 7.5 (Poulin, 2010)
Rotary vacuum washer & decker	0.58 - 0.72 (Turner, 2001)	E_{12} 2.5 - 4.0 (Smook, 1994)
Wash press	0.83 -0.92 (Turner, 2001)	E_{10} 4.0 - 5.0 T.M. Poulin, 2010)
Compact Baffle Filter	0.80-0.85 (Turner, 2001)	E_{10} 5.6 - 7.2 (Bryntesson et al., 2002)
Chemi-washer		E_{10} 2 -2.5 per stage (Krotscheck, 2008)

4.8 Summary

Washing is commonly done in the brown stock department and in the bleaching department. There exist some parameters to evaluate the performance of washing, which are: equivalent displacement ratio, (EDR), Modified Norden efficiency,(E_{st}), and yield (Y). However, the indicator used for this analysis was the EDR alone. The Modified Norden Efficiency(E_{st}), has the drawback that it can be used for comparison only when the DF is equal to 2.5. The yield [%], does not have a value to compare against the different types of washers. The washers with typically higher efficiencies are wash presses, drum displacers, compaction baffle filter, and belt washers. The variables with a more significant effect in washing efficiency are shower flow, shower temperature, drum speed, which all have an impact on the pulp mat thickness, and the feed and discharge consistency.

CHAPTER 5 METHODOLOGY

The following diagram represents the overall methodology, which consists of four steps, which mainly are: simulation and validation, energy characterization for mill A, washing performance analysis for mills A, B and C and energy and water saving projects for mills A, B and C. The details are presented as follows.

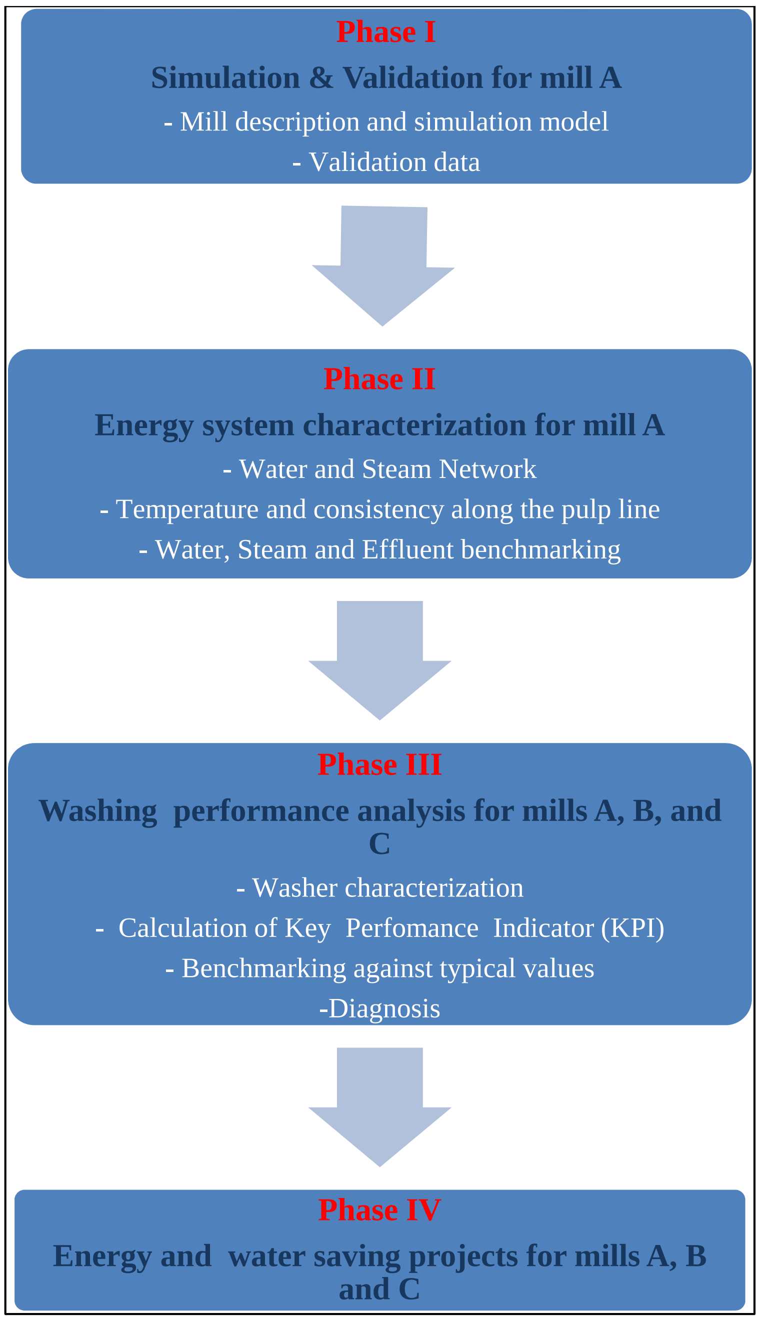

Figure 5-1: Overall methodology

5.1 Phase I - Simulation and Validation

Phase I consists of two parts, the mill description and validation.

The mill description consists of a description of the products, production, type of feed stock, type of fuels and boilers used for electricity generation, water consumption, effluent production and steam consumption for the whole process. Every mill department is described, as well as the main equipment of each department.

The model validation consists of the validation of steam and water consumption and effluent production globally.

5.2 Phase II - Energy systems characterization

The energy system characterization consists of the representation of the water and steam networks, the screening tool called temperature and consistency along the pulp line, water and steam consumption benchmarking, and effluent production benchmarking.

Water network

On the top, the start point is the fresh water. The inlet fresh water is used in the steam department in order to assure input to the deareator and previous heating in the recaustification department.

The rest of the inlet fresh water is used to provide warm and hot water. The warm and hot water tanks are the key points of the water network. In order to verify the closure of the balance, a water balance will be performed after the water network.

Steam network

The recovery boiler, boiler, and deareator are the key equipment in the steam network. The deareator is the piece of equipment that produces hot water without air bubbles at high pressure; the deareator inputs are hot water from the main condensate return tank and low pressure steam. In a representation of the boiler high pressure steam production medium and low pressure steam is distributed along the process line and once it is used the steam is collected in the fresh water condensate tank where it usually is used to feed the deareator.

Temperature and consistency along the pulp line

This screening tool will be used to determine the point where dilution with water or white water is done and steam injection is performed and their effect on the temperature of the pulp along the pulping departments.

Process benchmarking.

Global water consumption in the mill and by department will be benchmarked against average water consumption in pulp and paper mills in North America.

Global effluent production in the mill and by department will be benchmarked against average effluent production in pulp and paper mills in North America.

Global steam consumption in the mill and by department will be benchmarked against median energy consumption in pulp and paper mills in Canada.

5.3 Phase III - Equipment performance analysis

This phase is divided into Base Case Analysis and Performance Diagnosis. In the Base Analysis a characterization of the washing equipment is done. The main washing equipment is as follows: continuous digester washing zone, pressure diffuser, atmospheric diffuser -1 stage and 2 stages, rotary vacuum drum, wash press, and compaction baffle filter.

Once the characterization of brown stock section washers has been completed the equipment performance indicators are calculated.

After the benchmarking of the typical KPIs has been prepared, an analysis of the causes of any abnormal equipment performance will be addressed.

5.4 Phase IV - Energy and water saving projects

The last phase of the methodology is the proposal of water and energy projects, by the addition of controllers for certain parameters, the water reutilization from other part of the process, etc.

CHAPTER 6 CASE STUDIES

5.1 Mill A Process description

Mill A is situated in eastern Canada and has an average production of 560 air dried tons per day (adt/d) of dissolving pulp, with the feedstock consisting mainly of maple, birch, and aspen. Dissolving pulp is the raw material required for the production of viscose and other chemical derivatives.

Fresh water is taken from a nearby river at a consumption of 87.5 m^3/adt, resulting in a mill effluent generation of 67 m^3/adt. The steam consumption is 28.2 GJ/adt and is produced by three types of fuels: black liquor, fossil fuels, and biomass.

Table 6-1: Mill A Characterization

Production	
Product	Dissolving pulp
Type of feedstock	Hardwood: Maple, Birch and Aspen
Digester type and yield	Batch – 41 %
Production	560 adt / day
Fuels used:	NG, bark and oil
Utility system	
Number of Recovery Boilers	1
Number of Power Boilers	1
Electricity generation	20 MW
Steam levels	HP 6097 kPa, MP 1032 kPa, LP 529 kPa
Type of turbine	Backpressure

An overview for each section of the mill is presented below.

6.1.1 Pulping

The cooking process comprises the following stages: chip fill, prehydrolysis, neutralization, cooking, dumping, and blowing.

The production of dissolving pulp requires two additional stages in comparison to a typical Kraft process, prehydrolysis for hemicellulose extraction, and neutralization. These two processes are described in detail.

The chips are fed to the digester using a blower system. The aim of the blower system is to remove the air from the digester during the chip fill period. The vacuum created in the digester facilitates the flow of the chips, prevents blow back of the chips and promotes the formation of a homogeneous chip pile in the chip bin.

The aim of the prehydrolysis step is to dissolve and remove the hemicellulose in the fiber. This is achieved by first introducing steam into the digester with the chips, and allowing the temperature to reach 170°C. Once the digester is full of chips, low pressure steam is injected to remove the air in the digester. After a temperature of 135°C is reached, medium pressure steam is injected to achieve 170°C.

The prehydrolysis reaction creates an organic acid with a final pH of approximately 3.0. The next step after prehydrolysis is neutralization, where the low pH material needs the acidity neutralized. It is sent to a neutralization tank, and then a mixture of hot black liquor and white liquor are sent to the digester to displace the organic acid. During the neutralization step, a certain amount of neutralization liquor is injected into each digester. At the end of this stage the digester reaches 130°C to 140°C and has a pH of 11 – 12. The next step is the cooking where alkali is added.

The cooking operation is a natural continuation of the neutralization step and cooking liquor is supplied by the same four lines. Once the cooking process is finished, the digester is ready to be emptied and steam is injected to clean the digester and to send the pulp to blowdown tanks where it is cooled to below 100°C. The cold pulp is then sent to the knotters and washers.

Table 6-2: Summary of key aspects for pulping department for mill A

Parameter	**Description and quantity**
Chips feed	1060 adt/ day
Yield	41%
Water consumed	8.7 m^3/adt
Steam consumed	8.8 GJ/adt

6.1.2 Knotters, brown stock washers and screeners

Pulp coming from the blow tank is fed to the primary knotter, and the knotter “accepts” are sent to the first brown stock washer. The rejects from the primary knotter are cascaded to the secondary knotter and the secondary knotter “accepts” are recirculated to the primary knotter.

After the pulp has been processed by the knotters, it is washed in a counter current flow with evaporation condensate.

Table 6-3: Summary of key aspects for knotters, washers and screeners in mill A.

Parameter	**Description and quantity**
Knotters	Two primary and one secondary knotters.
Brownstock washers	One compaction baffle filter (CBF), three rotary vacuum drum and one decker
Screeners	Two primary screeners, one secondary screen and one tertiary screen
Cleaners	A primary cleaner, a secondary cleaner, and a low density cleaner.
Water consumed	8.7 m^3/adt
Steam consumed	0 GJ/adt

6.1.3 Bleaching

The bleaching sequence is D0-Eop-H-Eph-D2. The chemicals used are as follows: ClO_2 for the D0 stage, - NaOH -H_2O_2 and O_2 for the Eop stage, NaOCl for the H stage, NaOH, O_2 and NaOCl for the EpH stage and NaOH for the D2 stage, as shown in **Table 4-1**. All the washers used in the bleaching section are of the rotary vacuum drum design.

D0 stage

After the pulp has been washed, ClO_2 is used in the Do tower at a temperature of 45°C. The pulp is then washed in a rotary vacuum drum, producing a pulp of 14% consistency. A simple schematic of the Do stage is presented in **Figure 6-1**

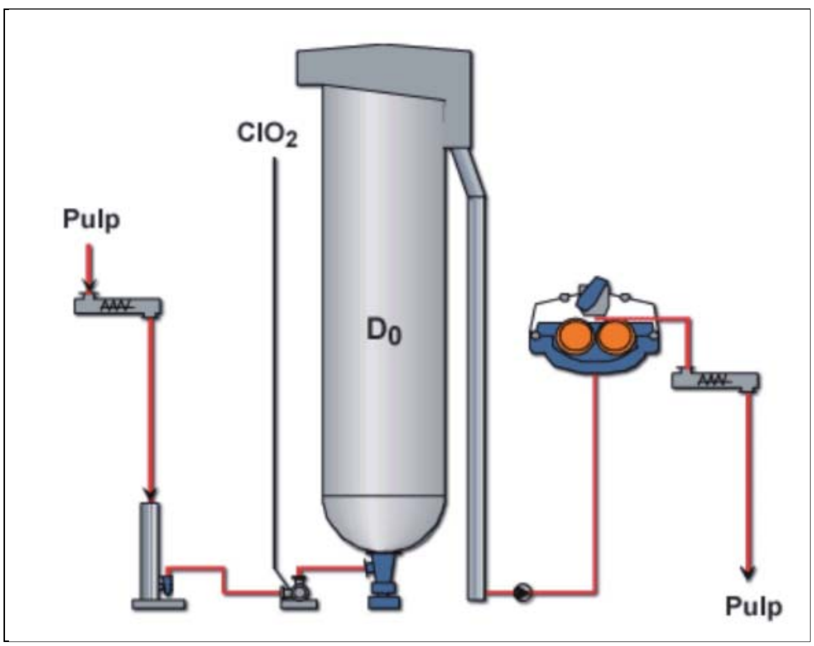

Figure 6-1: Sequences D0, and D2, used with permission of Metso (Kalander, 2008)

EOP stage

After the pulp has been washed in the D0 stage, NaOH is first added, after which steam is injected to achieve a temperature of 72°C prior to the injection of H_2O_2 and O_2. The pulp is held in the EOP tower and once the reactions are completed, the EOP washer filtrates are injected to dilute the pulp to 4% consistency. Finally, the pulp is washed in a rotary vacuum drum producing a pulp with an outlet consistency of 14%.

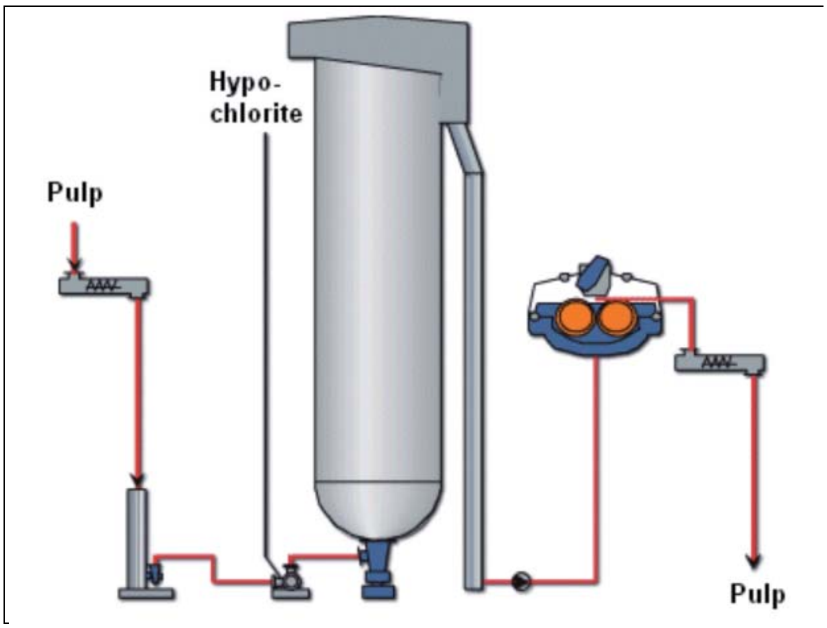

Figure 6-2: EOP sequence, used with permission of Metso (Kalander, 2008)

H stage

After the pulp has been washed in the EOP stage, NaOH and H_2O_2 are injected, the pulp is held in the H tower until the reactions are complete, and the H washer filtrates are added to dilute the pulp to 1.65% consistency. Finally, the pulp is washed in a rotary vacuum drum producing a pulp with an outlet consistency of 14%.

EPH stage

NaOH is injected in the pulp stream prior to the injection of H_2O_2 and NaClO. Prior to feeding the pulp to the Eph tower, low pressure steam is injected to achieve a temperature of 60°C. The pulp is held in the Eph tower until the reactions are completed. After the pulp has been processed in the EpH tower, it is diluted to 1.65% consistency to be fed to the Eph washer, which produces a pulp with a 14% consistency.

D2 stage

Steam is injected to achieve a temperature of 78°C, after which ClO_2 at 15°C is injected to the pulp before it is sent to the D2 tower where the pulp is held. After the pulp has been processed, D2 washer filtrates are used to dilute the pulp to 1.65% consistency. Once the pulp has been diluted, it is fed to the D2 washer, producing a pulp at 14% consistency. Once the pulp has been washed, it is stored in the bleached stock storage, ready to be sent to the pulp machine.

Table 6-4: Summary of key aspects in bleaching section for mill A.

Parameter	**Description and quantity**
Sequence	D0-Eop-H-Eph-D2
Type of washers	Rotary vacuum drum
Water consumed	23.67 m^3/adt
Steam consumed	2.42 GJ/adt

6.1.4 Pulp machine

After the pulp has been bleached, it is stored in bleached stock tanks. After the pulp is screened through two primaries and one secondary screen, then four cleaners and one fiber mixer cleaner, it is passed through two thickeners and then diluted down to 1.3% consistency in the approach flow to the head box. Once the pulp is injected onto the formation zone, the web is passed through three presses prior to entering the dryer section where the solids content is 48% consistency. A Flakt type dryer using heated air is used to dry the pulp mat to a solids content of 90%

Table 6-5: Summary of key aspects for a pulp machine department in mill A.

Parameter	**Description and quantity**
Screens	Two primaries and one secondary
Cleaners	Two primaries, one secondary, one tertiary , one quaternary and a Fiber Mixer RCC cleaner
Thickeners	Two, one slusher and one thickener
Formation table	Fourdrinier
Dryer type	Flakt
Cs % product	90 %
Water consumed	8.54 m^3/adt
Steam used	2.29 GJ/adt

6.1.5 Evaporation

The evaporation section consists of five stages. The first two stages are divided into two evaporation units and the three final stages each have three evaporation units. Two surface condensers use the steam produced in the last evaporation stage and mix it with fresh water at 1.5°C to produce warm water at 45°C.

Table 6-6: Summary of key aspects for the evaporation department in mill A.

Parameter	**Description and quantity**
Type of evaporators	Rising film tube
Number of effects	5
Number of units	7
Area	8,721 m^2
Economy	4.2 [kg H_2O evaporated/kg of steam injected]
Ds in weak Black liquor	19.2%
Ds at last stage	54.4 %
Concentration method	Cascade direct contact
Ds after concentration	68.5 %
Water consumed	0.85 m^3/adt
Steam consumed	3.13 GJ/adt

6.1.6 Recausticizing

The aim of the recausticizing department is to maximize the regeneration of chemicals used in the delignification process (NaOH and Na_2SO_4). White liquor is produced in the NaOH – CaO process via the following chemical reaction equations:

Lime Slaker CaO (lime klin) + $H_2O \rightarrow Ca(OH)_2$ (12)

Causticizer $Na_2CO_3 + Ca(OH)_2 \rightarrow NaOH + CaCO_3$ (13)

Table 6-7: Summary of key aspects for chemical recovery

Parameter	**Description and quantity**
Water consumed	18.6 m^3/adt
Steam consumed	0.83 GJ/adt

6.1.7 Recovery boiler

The recovery boiler uses black liquor at 60% dissolved solids content as a fuel to produce steam, with the resulting smelt being sent to the recausticizing department to regenerate green liquor. The stack gases are passed through an electrostatic precipitator to remove dust and sulfuric components, and are then passed through a heat exchanger to produce warm water where the gases are finally sent to atmosphere at approximately 80°C.

Table 6-8: Summary of key aspects for the chemical recovery

Parameter	**Description and Quantity**
Steam produced	150 t/h

6.1.8 Steam plant

The steam plant produces three levels of steam, HP, MP and LP steam, by using one power boiler and one recovery boiler. Two two-stage turbines produce up to 20 MW of electricity.

Table 6-9: Summary of key aspects for the steam plant in mill A.

Parameter	Description and quantity
Recovery boiler	1
Fuel used	Black liquor
HP steam produced	150 t/h
Steam used in power boiler	6 t/h
Power boiler	1
Fuel used	Bark and NG
HP steam produced	90.67 t/h
Steam used in power boiler	0.9 t/h
Power generation	
Power produced	20 MW

6.1.9 Chemical preparation

Chlorine dioxide is produced on site in a chlorine dioxide generator and a heat pump is used to cool the ClO_2 to a temperature suitable for the process.

Table 6-10: Summary of key aspects for chemical preparation in mill A.

Parameter	Description and quantity
Water consumed	1.84 m^3/adt
Steam consumed	0.0 GJ/adt

6.1.10 Mill A simulation model

The simulation model was based upon P&ID's from the partner mill for the structure. Daily data extracted from the PI System was also used for flow rates.

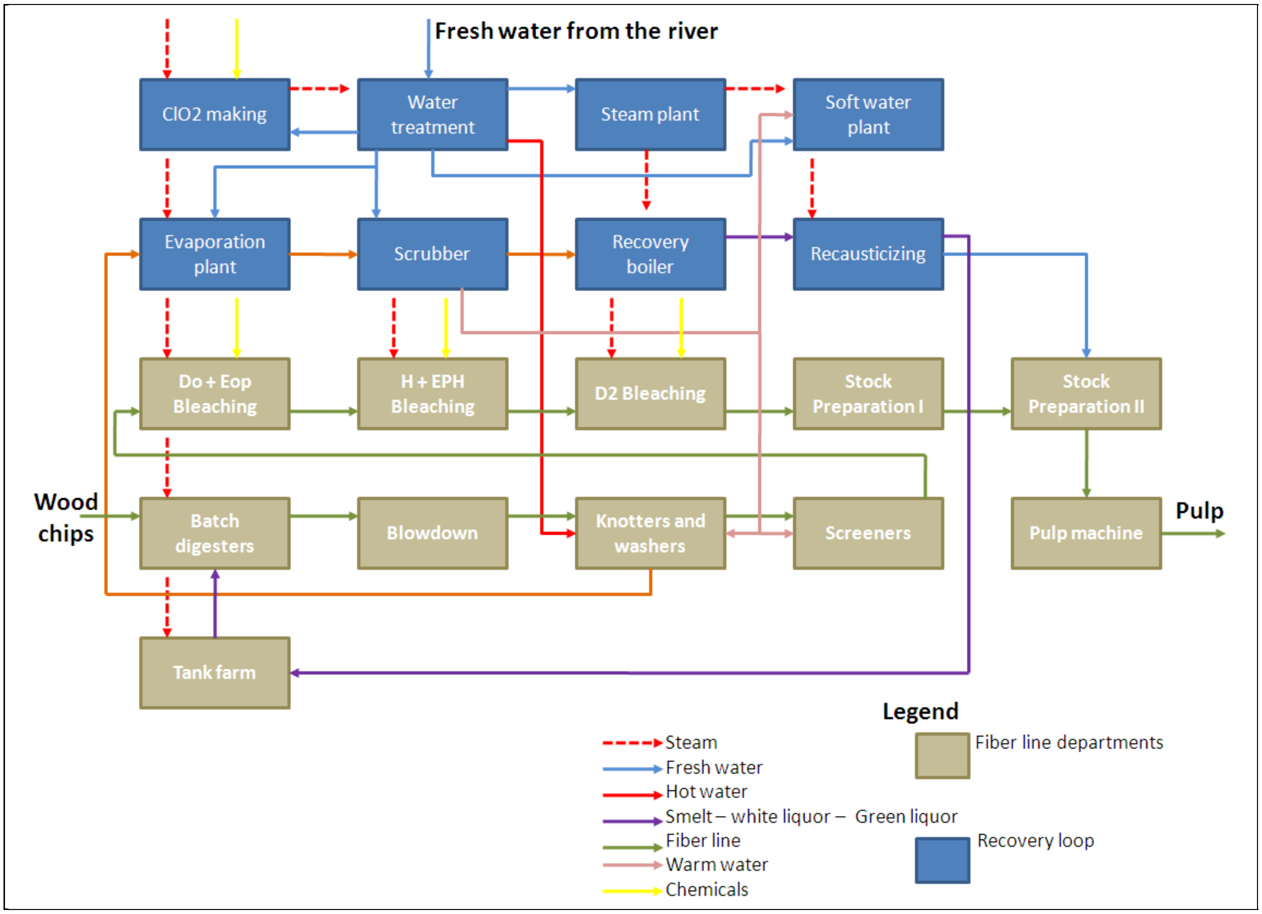

Figure 6-3: Schematic of simulation model for mill A.

The simulation model was built in CadSim Plus ® is a Canadian simulator for the pulp and paper industry developed by Aurel Systems® and combines a drawing interface with a dynamic process simulation engine. This simulation software has libraries with specific pulp and paper modules and components.

CadSim Plus ® is a sequential simulator (SMS) with a solution method for dynamic solving of flow networks and pressure flow networks. The unit operation, stream and control components as well as other functions are implemented as dynamic link libraries.

The model is configured through a graphical user interface showing flow sheets, which resemble P&IDs very closely, and it also has the capability to exchange data with Microsoft Excel, which allow the user to make custom inputs, calculations, and graphs.

Washing modules

In the model built in Cadsim Plus ®, some specifications must be entered, such as typical dilution factor and the typical displacement ratio for each washer. The typical displacement ratio is a performance parameter that needs to be provided to the model software for each washer. The value of the DR specified for every washer is presented in **Table 7-4**.

The equations to evaluate the washing performance are the same for the different washers with the difference in the washing efficiency being due to the type of equipment and the operation conditions.

6.2 Validation

In the validation of the data and model, a comparison has been made from the results of the model in Cadsim Plus ® and the values taken directly from the mill for both steam and water flow. The flows of the entire mill as well as the individual departments were analyzed. For both water and steam flows, the biggest difference between the simulation and mill data was 10%, showing that the simulation and mill data were in good agreement. The tables can be found in the Appendix 5

6.3 Characterization of mill A

The characterization of the process consisted of several tasks:

-Development of water and steam network: identification of all the water and steam consumers.

-Construction of temperature and consistency profiles: identification of dilution points where cold water or steam is used.

-Benchmarking: Comparison between the water and steam of the complete process and by department to identify the departments with enhancement opportunity areas.

6.3.1 Water Network

The water network of the process was divided into three parts: water production (demineralized or conditionated), water consumption and effluent production. The water is used at three temperature levels: cold (2°C), warm (34°C) and hot (74°C). Warm water is produced in the surface condensers of the evaporators and the scrubber of the recovery boiler. Hot water production is accomplished by heating the warm water with utility steam. A representation of the water network for mill A can be found in **Figure 6-4**. The details for the water network are given in Appendix 1.

6.3.2 Steam Network

The steam network of the process was divided into three parts: steam production, steam utilization and condensate recovery. There are three pressure levels for steam: high pressure (HP) at 6097 kPa, medium pressure (MP) at 1032 kPa and low pressure (LP) at 529 kPa. The high pressure steam is produced in the boilers and then it is depressurized in a two stage back pressure turbine, producing power, and also through throttle valves. The condensate recovery rate is 48%. The details for the steam network are given in Appendix 2.

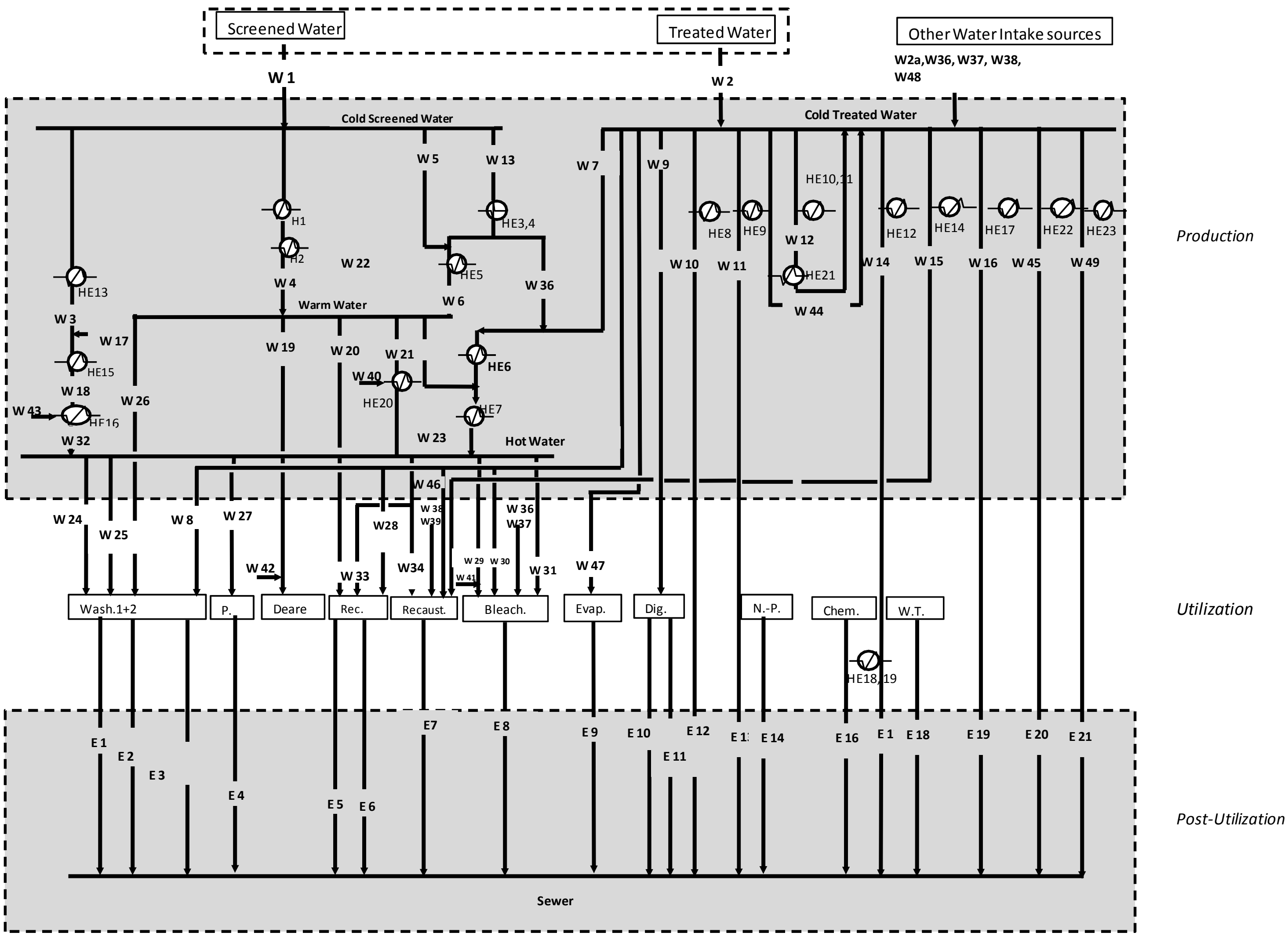

Figure 6-4: Mill A Water Network

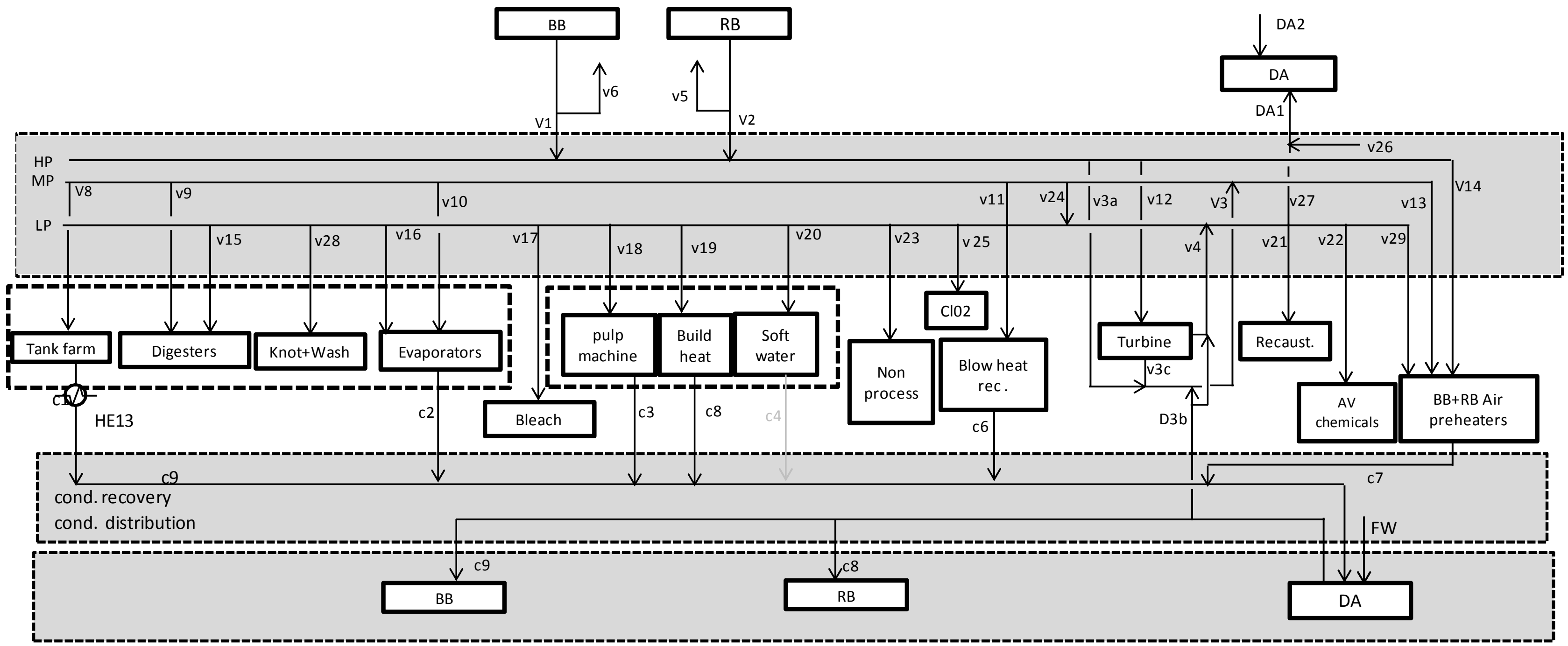

Figure 6-5: Mill A Steam Network

6.3.3 Process benchmarking

The process benchmarking identifies the inefficiencies regarding water and steam consumption and effluent production globally and for each department. In this section, there will be an overview of the complete energy, water, and effluent benchmarking.

Energy

The energy benchmarking was based on steam consumption. In the **Figure 6-6** the difference in steam consumption between mill A and North American and European mills built in the 1990's can be seen.

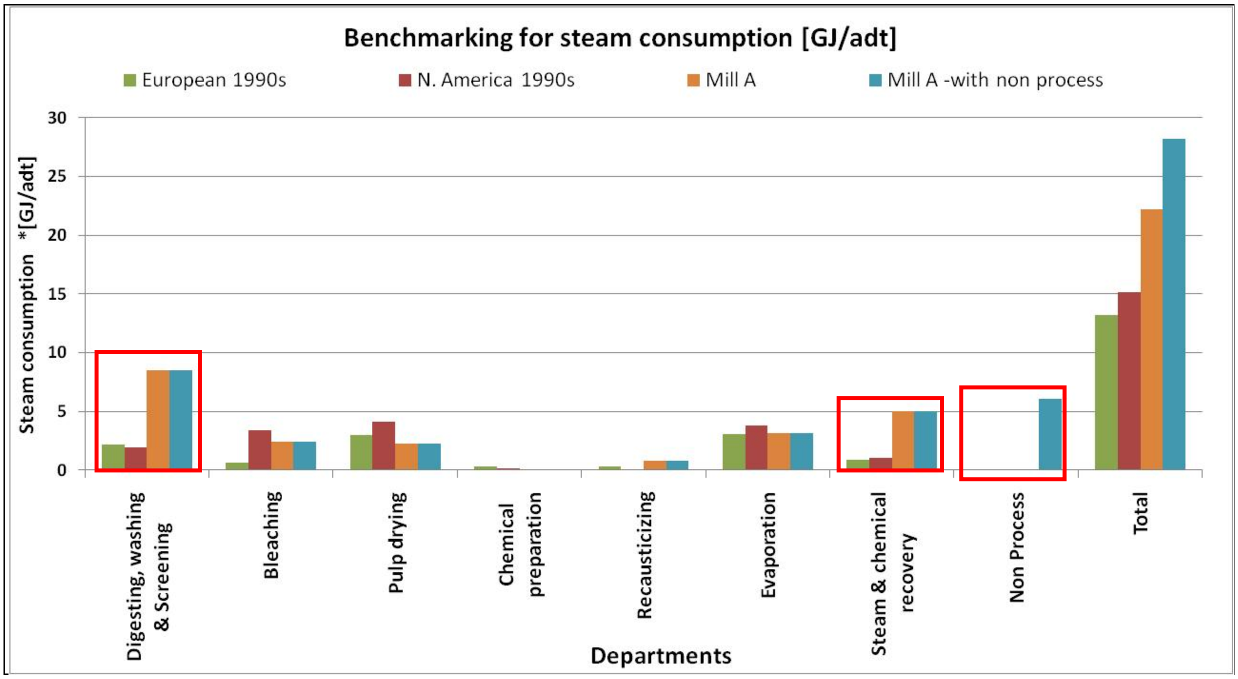

Figure 6-6: Mill A Benchmarking for steam consumption.

Overall steam consumption for process in the mill is 22.2 GJ/adt and 28.2 GJ/adt, including the steam used in building heating. Steam consumption in pulping, washing, and screening is 8 GJ/adt, which is higher in mill A than for the benchmarked values. The reason for this is that the dissolving pulp process requires more energy than the typical Kraft process. Bleaching in the mill requires 2.4 GJ/adt, which is less that the average steam consumed in North American mills built in the 1990's and higher than European mills built in the 1990's.

The pulp drying and evaporation departments require 2.3 GJ/adt, and 3.1 GJ/adt, respectively, which is less steam than used in North American and European mills built in the 1990's.

The recausticizing department consumes 0.83 GJ/adt, which is higher compared to the value of European mills, and for North American mills the average is 0.0 GJ/adt in this department. The large consumption of steam is due to the steam required to increase the temperature of cold water being used for washing and steam used to produce hot water.

The steam and chemical recovery section consumes 5 GJ/adt, which is higher than the other benchmarks, mainly because half of the steam consumed is used in the deareator and the rest is used in the air pre-heaters to heat up the air used in the boilers.

Water

The water benchmarking is obtained based on information from Chandra (1997). The data is average data from mills designed in the 1960’s, 1980’s and 2000’s.

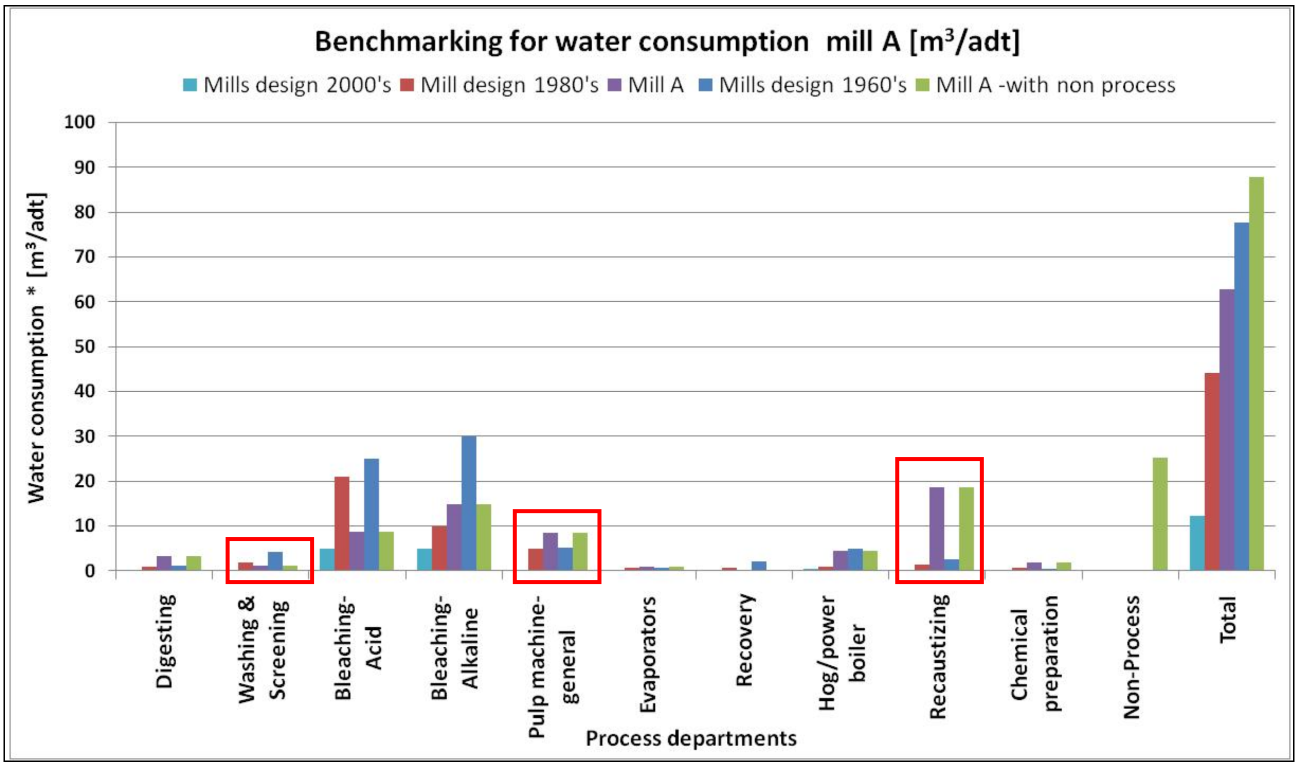

Figure 6-7: Mill A Benchmarking for water consumption.

The overall water consumption of the mill, including non-process water is 88 m^3/adt, value that is higher than all of the benchmark values, as it is shown in **Figure 6-7**. Water consumption for the process is 62.7 m^3/adt, which is less than the consumption of a mill designed in 1960’s.

The water consumption in the pulping stage is 3.2 m^3/adt, which is higher than all the references except for mills designed in the 2000's. This water is used mainly in the tank farm, hot water accumulator and in ternary condensers to remove non condensable gases.

The water consumption in the washing and screening section is 3.8 m^3/adt, which is higher than all the benchmarks expect for the oldest mill designs. In this section, the water is used mainly in the tank farm, the hot water accumulator, in ternary condensates to remove non-condensable gases and in cleaners.

The water consumption in the acid bleaching section, representing the water used in stages DO and D2 of the mill is 8.8 m^3/adt, which is lower than all the references, except for mills designed in the 2000's.

The water consumption in the alkaline bleaching section, representing the water used in the EOP, EpH and H stages of the mill is 14.8 m^3/adt, which is lower than 1960‘s mills.

In the evaporators the water consumption is 0.85 m3/adt, higher than all the references, but it does not represent a high water consumer department. The high consumption is due to water used in the ejector train.

The water consumption in the recovery department is 0.32 m^3/adt, which is very low, but close to values for mills designed in the 2000's. The accounted water is the water injected in the scrubber and used in the dregs washer.

Hog and power boilers consume 4.5 m^3/adt of fresh water to make up water to the deareators, a value that is higher in comparison with 2000's and 1980's mill designs.

The recausticizing department consumes a very large amount of water, 18.59 m^3/adt, which is higher than all the references. The reason for the high consumption is that approximately 60% of the water is used in the scrubber; the rest is used to cool down the lime kiln and in the hot water tank.

Effluent

The water benchmarking was made based on information from Turner (2001) and a report by Greenpeace (Johnston et al., 1996). The data is average data from mills designed in the 1960's, 1980's, 1990's and predicted future mill designs. The total mill effluent generation is 87 m^3/adt, which is higher than the references. If the effluent production without the non-process stream is compared to mills designed between 1960's and 1980's the amount of effluent is below the average. Compared to mills designed in 1990's and possible future designs it is far above the average generation, as can be seen in **Figure 6-8Erreur ! Source du renvoi introuvable.**. An explanation of the effluent benchmarking will be presented in detail.

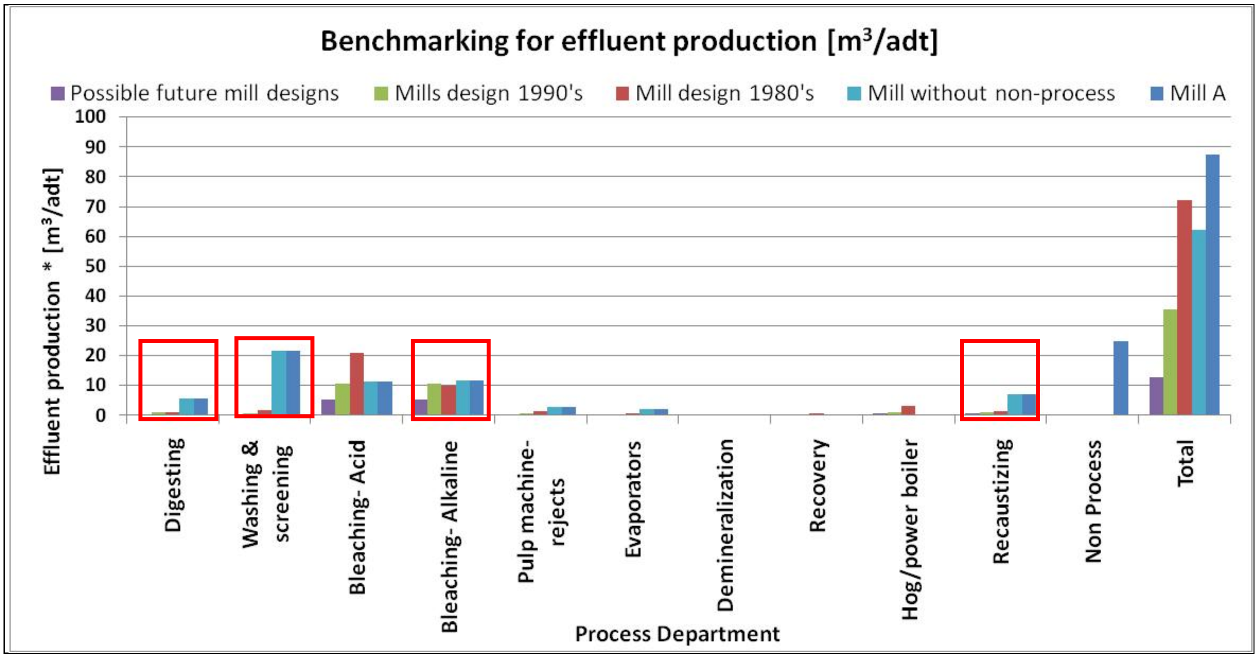

Figure 6-8: Mill A Benchmarking for effluent production.

The departments generating effluent are pulping, washing and screening, bleaching, recausticizing, and non process water. A detailed description of these departments is presented below.

The pulping department has an effluent production of 5.6 m^3/adt, a value that is higher than the references. The main reason is the overflow of the warm water tank, dirty condensate, and the water used in the tertiary exchanger.

The washing and screening departments produce 21.4 m^3/adt, a value which is very high compared to the reference values. This is mainly due to the overflow of the last brown stock sealed tank, which accounts for 16.5 m^3/adt; the rest of the flows are rejects from screens.

The effluent from acid bleaching is 11.4 m^3/adt, which is produced from the sealed tanks of the Do and D2 overflows. The value is lower than the average value for mills designed in 1980's. The effluent produced from the alkaline bleaching is 11.6 m^3/adt, produced from the Eop, Eph and H bleaching stages and the value is higher than the other references.

The effluent produced in the recausticizing department is 7 m^3/adt, which is a higher value than all the references. This is due to the water used in lime cooling and the overflow of the weak wash storage sent to sewer.

The pulp machine rejects and the evaporator and boiler blow down present a very low effluent production.

6.3.4 Temperature and consistency along the pulp line

The temperature and consistency profiles are presented in **Figure 6-9**. The analysis of the two profiles has to be performed conjointly, because every dilution that reduces or increases the consistency has an associated change in temperature. In the temperature profile of mill A, three valleys are found in the washing, bleaching, and the pulp machine. The temperature reduction is produced because of pulp dilution with cold water, and the temperature increase is produced by direct steam injection. These changes are associated with washers. As a result of the benchmarking it was also found that washers consumed water in excess. Therefore, to optimize the washer performance, all the factors that affect the operation and the temperature of the streams involved in washing should be considered.

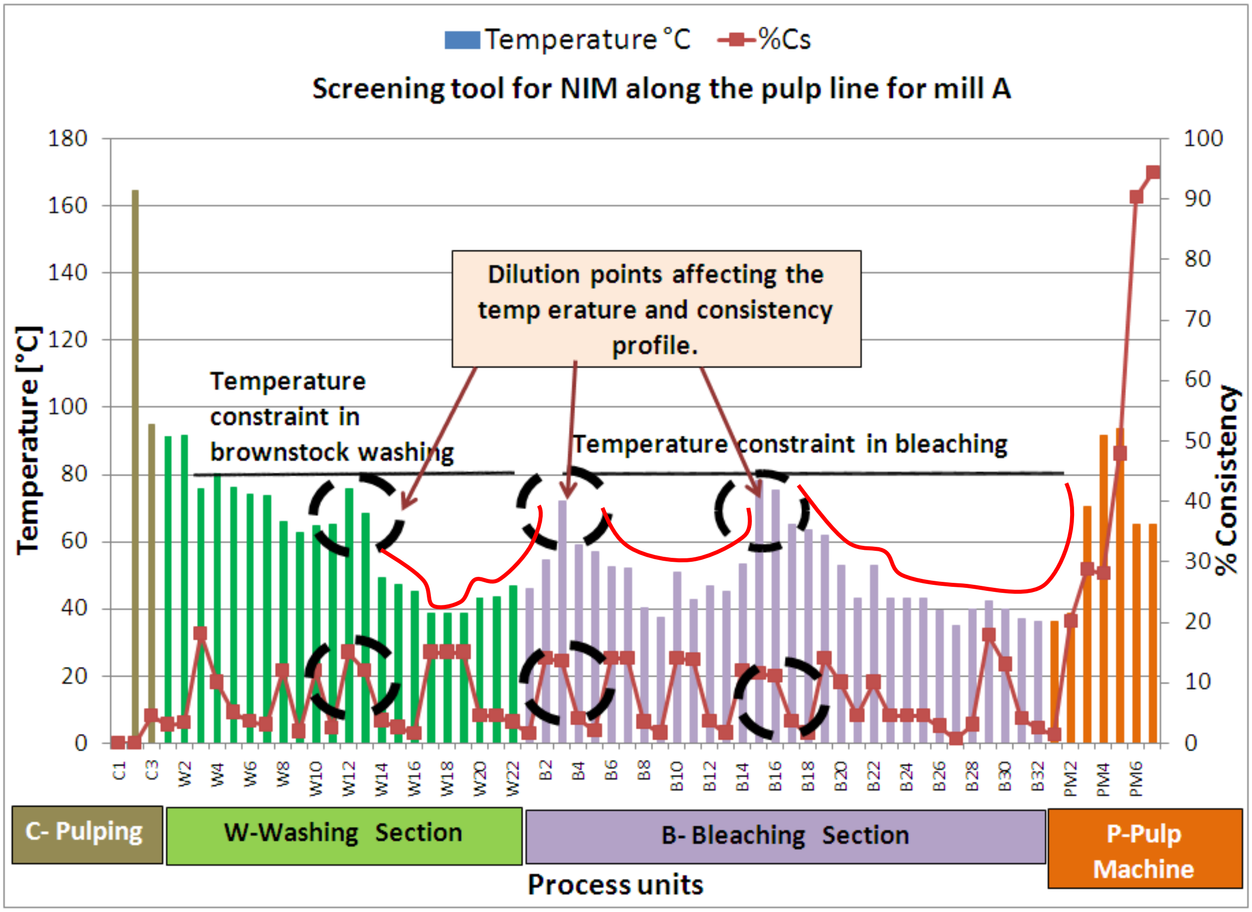

Figure 6-9: Temperature and consistency along the pulp line for mill A

6.4 Overall projects for mill A

For mill A, some of the energy and water projects were implemented. These projects are illustrated in the following figures with an explanation and illustration of both before and after the project implementation, annotated with the amount of water and energy savings.

Project 1 Recuperation of condensates from a heat exchanger in the digester department

In the current configuration exist a stream of fresh water used to remove heat from a BL steam through a heat exchanger, finally the water is sent to sewer at 80 °C. In the proposed scenario the alternative to return the clean water to the condensate tank, increasing the condensate return from 48% to 52 %. Also an effect in observed in the steam consumption in the deareator. The water and energy saving are 1.15 % and 0.45 % respectively.

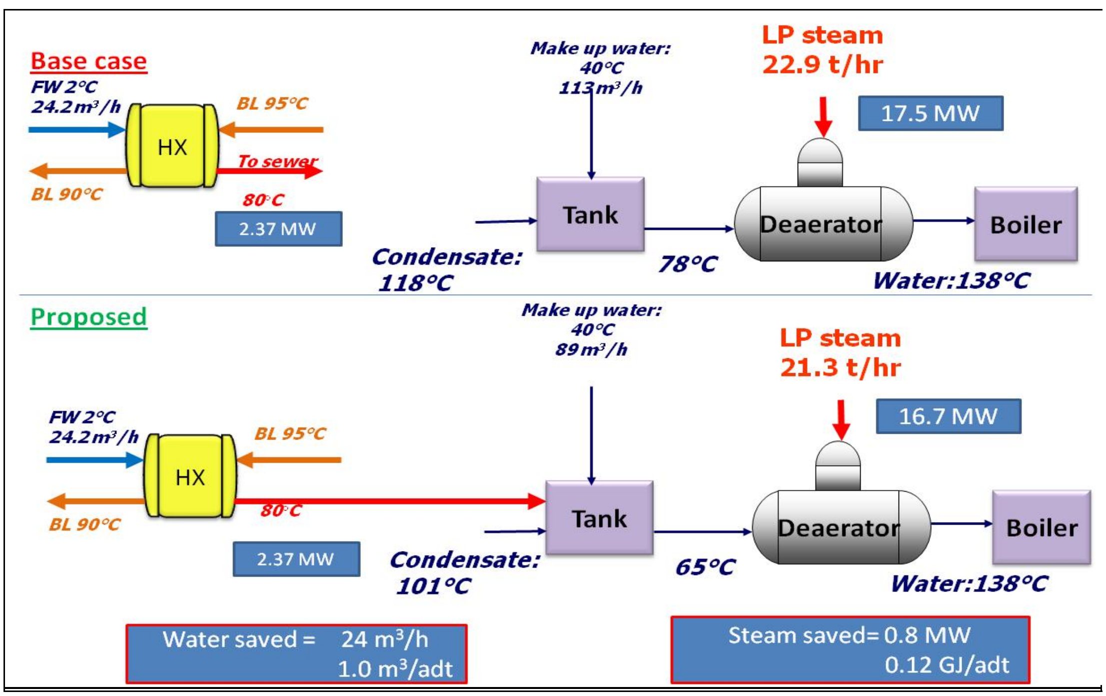

Figure 6-10: Overall projects for mill A - project 1

Project 2 Heat recovery from exhaust air in dryers

In the current configuration of the mill the exhaust air from the two sections of the dryers is sent to the environment at 88°C and 91°C approximately. In the proposed project the make-up water at 40°C is heated to 86°C with the energy obtained from the exhaust air from the dryers. The exhaust air from the dryers is cooled down up to 34°C. This proposed project does not have water saving. The energy saving is 3.3 % .

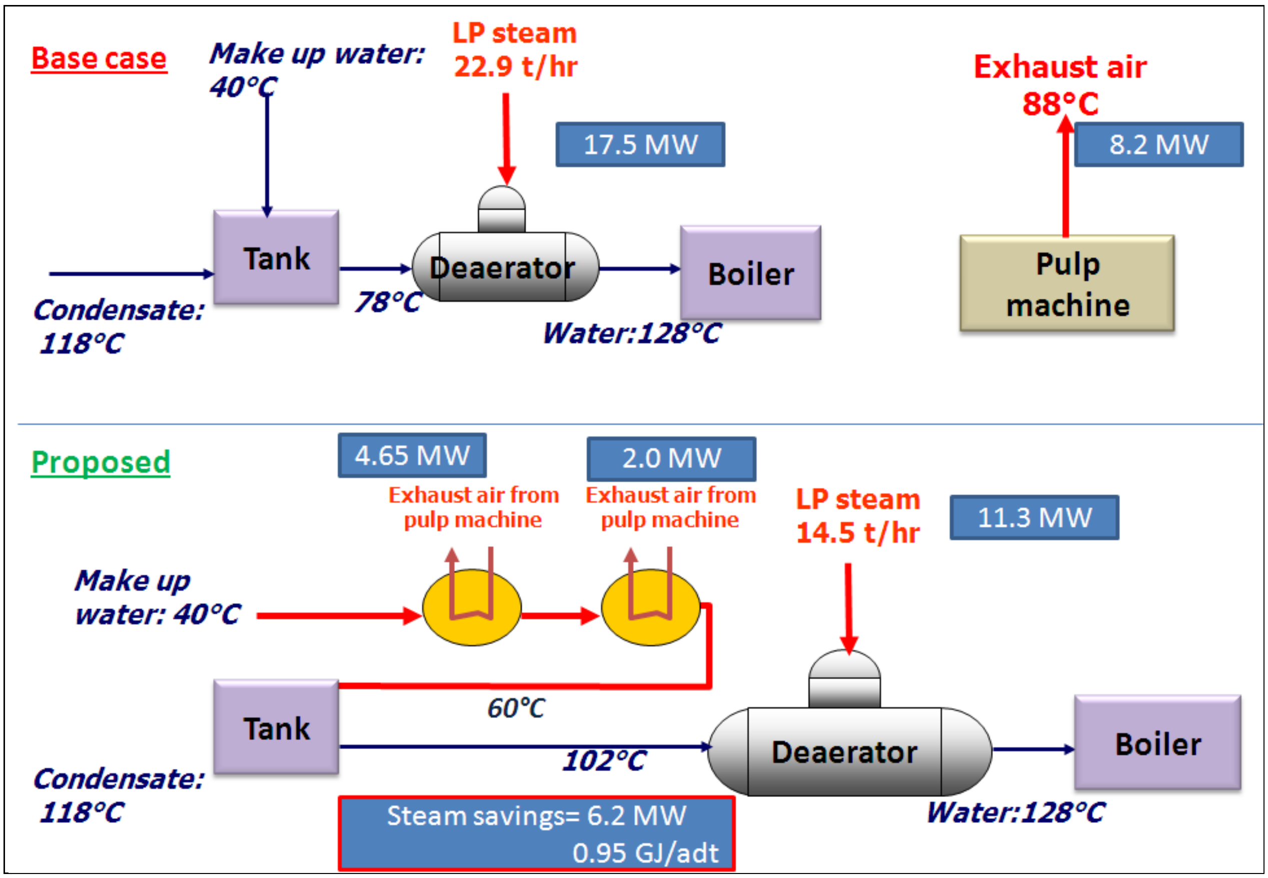

Figure 6-11: Overall projects for mill A - project 2

Project 3. Steam recuperation from flash tank in pulp machine to replace LP steam

In the pulp machine department there is a flash tank that is fed with condensate water at 529 kPa producting 1.75 t/h of steam at 130 kPa that is vent to the atmosphere. In the wire pit, tank below the pulp machine where the white water is received there is a injection of 1.6 t/h of low pressure steam. The proposed projects consist in the replacement of low pressure steam produced in the steam plant with steam produced in the flash tank This proposed project does not have water saving. The energy saving is 0.7 % .

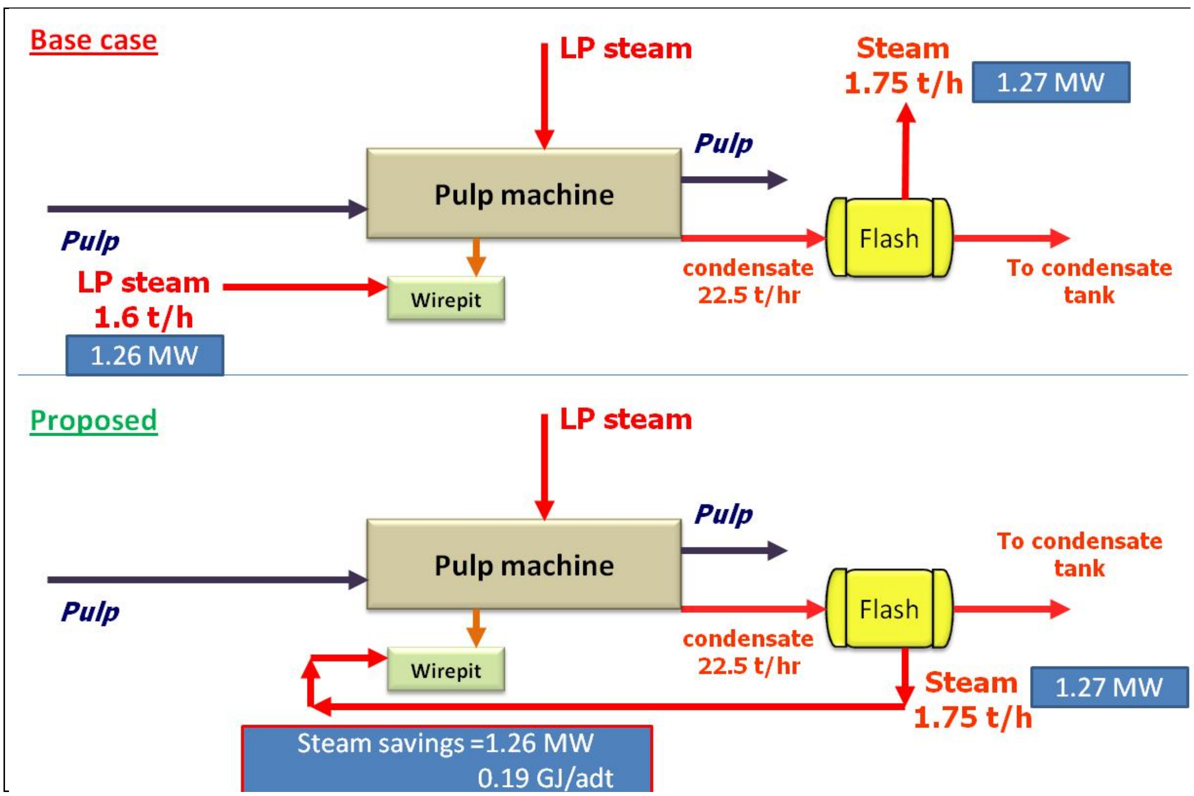

Figure 6-12: Overall projects for mill A - project 3

Project 4. Replacement of fresh water with warm water tank overflow in bleaching

In the actual configuration there is an overflow of 45-55 m3/h of warm water at 45 C sent to the sewer. In the bleaching department a flow of fresh water at 4C is injected in the seal tank, to mix with the filtrates and use it to dilute the pulp that is fed to the washer. The proposed project consist in the replacement of the fresh water for the overflow of warm water. The water and energy saving are 2.2 % and 0.55 % respectively.

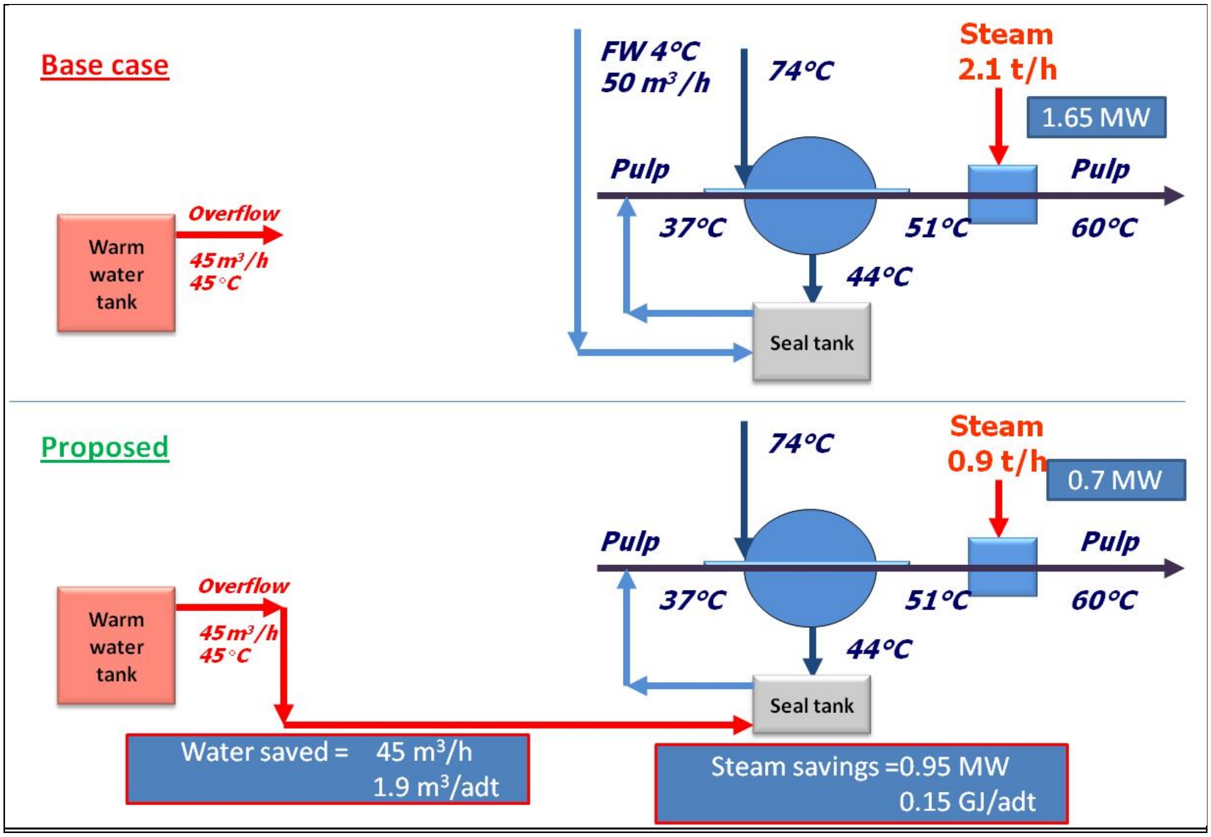

Figure 6-13 : Overall projects for mill A - project 4

<u>Project 5. Fresh water heat up with alkaline effluents</u>

In the current configuration there is an overflow in the 16.5 m^3/adt , which corresponds to 345 m^3/h in the last filtrate tank of brown stock washing.

In the stock preparation department, a department prior the pulp machine, the pulp is washed with water at 65°C. in two thickeners using 114 m3/h of water at 65°C. The thickener does not have a washing capability but it increases the pulp consistency. The filtrates produced in this section are sent to the white water tank , a port of it is sent to seal tank of the last stage of washing.

The proposed project is to reduce the amount of water used in the first thickener up to 20 m3/h, rhe effect observed in the simulation is a reduction in the overflow of 90 m^3/h . This proposed project does not have energy savings. The water saving is 4.6 % .

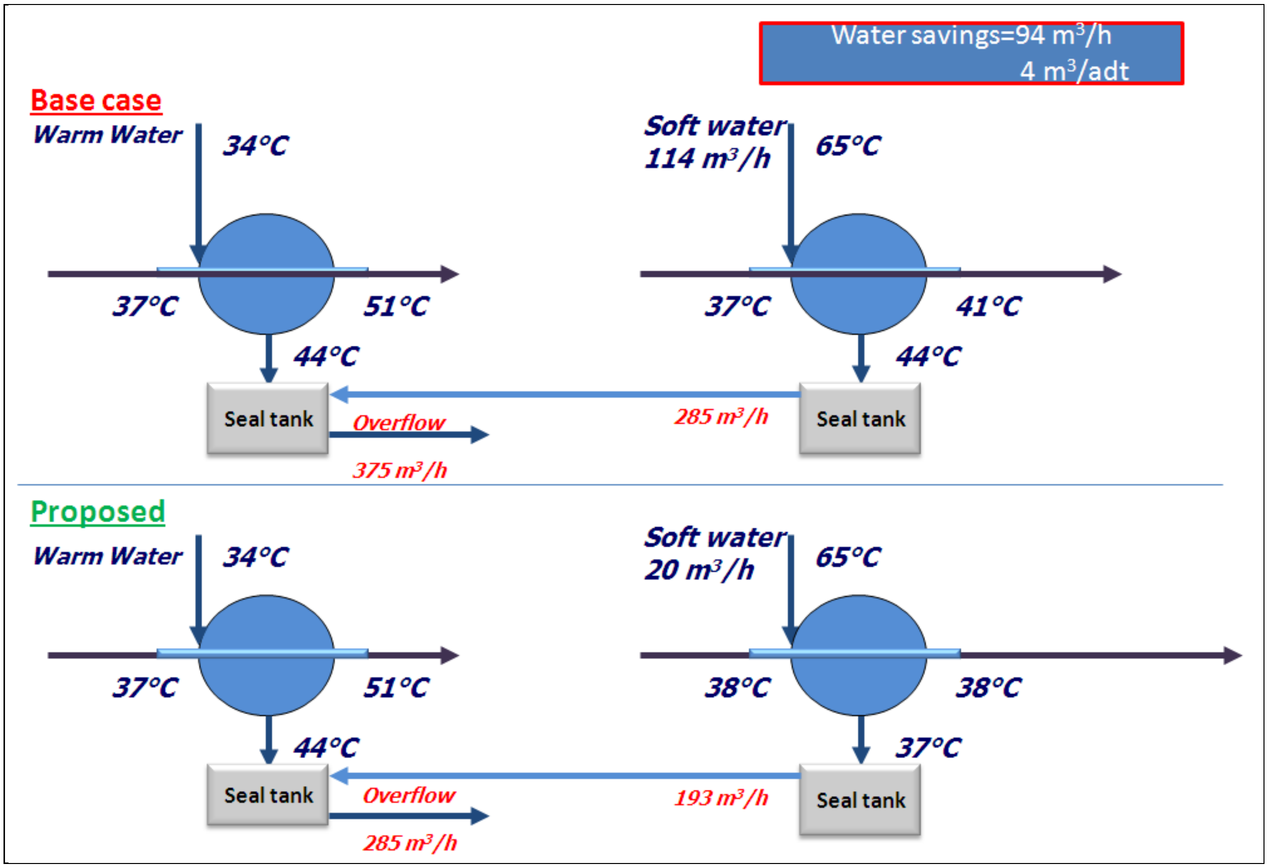

Figure 6-14: Overall projects for mill A - project 5

Project 6. Heat recovery from recovery boilers to heat up combustion air.

In the recovery department the stack gases from the recovery is passed through a cyclone , electrostatic precipitator, and heat exchanger to produce warm water. The cyclone and the electrostatic precipitator are used to remove the solids particles. The actual temperature of the stack gases is 70 °C.

In the current configuration medium pressure and high pressure is used to heat up the combustion air for the power boiler and recovery boiler. The temperature of the air is 23 °C and it is heated with medium pressure steam until 135 °C.

The proposed project is to recover the energy of the stack gases to heat up the combustion air. The temperature reached by the air is 70 °C, then medium pressure steam is injected to reach the 135 °C,

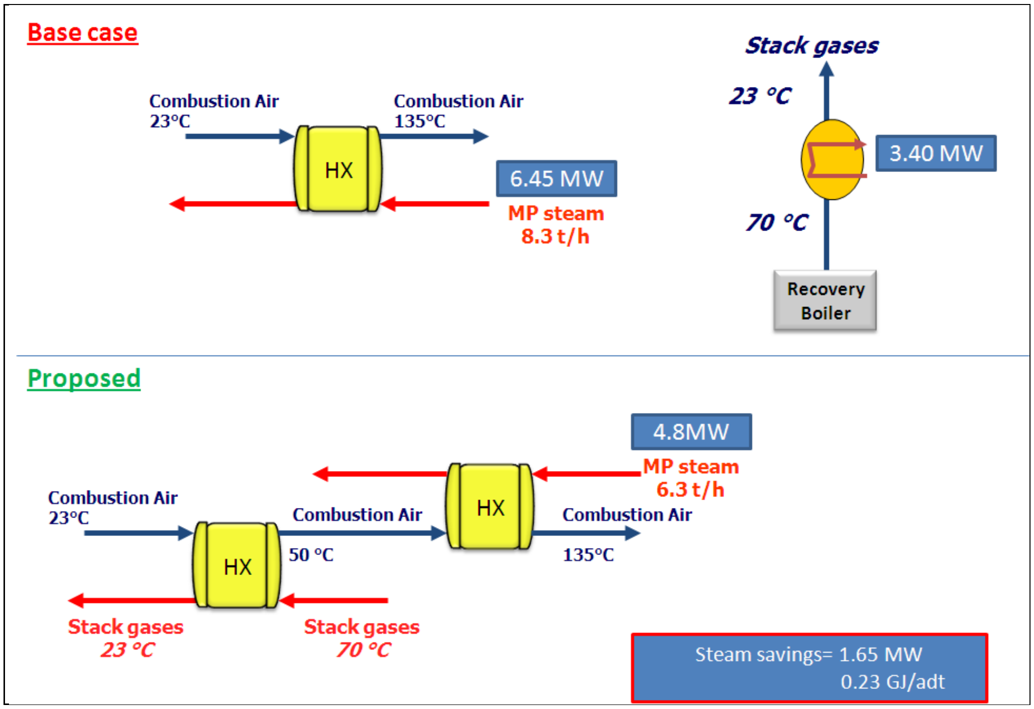

Figure 6-15: Overall projects for mill A- project 6

Summary of projects

The implementation of the six projects in mill A can add up a 5.9 % in steam saving and 8 % in water savings.. The most promising projects for steam savings are the project two and six, both can reach saving in steam up to 4.2 %. It is important to consider the project four and five to reach a water saving of 6.8 %. The details in the saving is presented in **Table 6-11**.

Table 6-11: Overall projects for mill A

Project	Steam saving			Water saving		
	[MW]	[GJ/adt]	[%]	[m^3/h]	[m^3/adt]	[%]
1. Recuperation of condensates from a heat exchanger in the digester department	0.8	0.12	0.45	24	1	1.15
2. Heat recovery from exhaust air in dryers	6.2	0.95	3.3	0	0	0
3. Steam recuperation from flash tank in pulp machine to replace LP steam	1.25	0.19	0.7	0	0	0
4. Replacement of fresh water with warm water tank overflow in bleaching	0.95	0.15	0.55	45	1.9	2.2
5. Fresh water heat up with alkaline effluents	0	0	0	90	4	4.6
6. Heat recovery from recovery boilers to heat up combustion air.	1.65	0.26	0.9	86		
Total	13	1.7	5.9	159	6.9	7.95

6.5 Brief description of Mill B

Mill B is situated in western Canada and has two production lines with an average pulp production of 1765 adt per day, with a softwood feedstock of mainly spruce and pine. One of the lines produces 805 adt/day and the other 960 adt/day, through two continuous digesters. The mill has two recovery boilers and two power boilers, producing three steam levels; HP 4300 kPa, MP 1150 kPa and LP 450 kPa. The high pressure steam is produced in the two power boilers and recovery boilers, and then it is depressurized in a two stage back pressure turbine and in throttle valves producing 49 MW of electricity. The fossil fuel used in the power boilers is natural gas, with bark also used. The water consumption of the mill is 42.5 m^3/adt and effluent production 47 m^3/adt. The steam consumption is 22.95 GJ/adt.

6.6 Brief description of Mill C

Mill C is situated in eastern Canada and has an average pulp production of 700 adt per day of Kraft and mechanical pulp. The feedstock is softwood (pine and spruce). The mill has one recovery boiler and four power boilers, producing a single steam level of 1286 kPa. The fossil fuels used are natural gas, with bark also used. The water consumption of the mill is 87.02 m^3/adt and effluent production 92 m^3/adt. The steam consumption is 21.7 GJ/adt.

6.7 Summary

As was evaluated in the benchmarking the departments with the most opportunity areas for steam savings are digesters, steam plant, chemical recovery, and non-process areas. The departments with the most opportunity areas for water savings are washing, pulp machine, recausticizing, and non-process. There are some departments where the effluent production can have some improvements, such as digesters, screeners, alkaline bleaching, and recausticizing. The implementation of the six projects in mill A can reduce the steam consumption up to 5.9 % in diminish the water consumption in a 8 % .

CHAPTER 7 RESULTS

In this chapter the results of the washing performance analysis of three mills will be presented. The analysis is presented in four sections: washer characterization, key performance indicators for brown stock washing, benchmarking against typical values and the diagnosis and proposal of energy and water projects to improve performance.

In the washing characterization section, the type and quantity of equipment is presented as well as the configuration of the washers. The equipment performance in the bleaching section is not to be analyzed due to the limitations of current equations and the method of calculation.

In the second section, the calculation of the key performance indicators for all brown stock washers is presented, in addition to the washing zone of continuous digesters.

The benchmarking section shows the measured performance indicators and compares them to typical values and analyzes the reason for any variations in performance.

Finally, the analysis links through to energy and water project proposals to improve performance for each partner mill.

7.1 Equipment performance analysis –Washing

Analyzing the performance of washing section is of the utmost importance as the washers have the highest water consumption of all departments in the mill. Washers in the brown stock washing and bleaching departments contribute to 74% of the water consumed in a typical Canadian mill built in the 1980’s, using the data provided by Turner (2001). The energy consumption for bleaching and evaporation accounts for between 42% for hardwood and 47% for softwood of the total steam consumed in Canadian mills (CIPEC, 2008).

7.1.1 Washer characterization

The washing characterization was performed for three different mills, identified here as mills A, B and C.

A brief explanation of the process for each mill is shown in the chapter Case studies. In the subsequent section here, an explanation of the quantity, type, of the washing equipment and operating conditions will be described for each mill.

Mill A

Mill A has a batch pulping process followed by screeners, cleaners, brown stock washing and bleaching. Washers are present only in the brown stock and bleaching sections.

- Brown stock section: 5 washers (one compaction baffle filter and four rotary drums).

Mill B

Mill B has two parallel production lines and the only interaction between them is that water is shared between the two lines.

  - Line A (Kamyr digester wash zone, Pressure Diffuser, 1 # and 2# drum washer, Decker and Wash press)
  - Line B (Kamyr digester wash zone, Pressure Diffuser two stages, Decker, wash press)

The inlet and outlet consistencies of the pulp and shower flow temperature for each of the two lines are described for both lines. It can be seen that while they operate similarly, one of the lines has an oxygen delignification stage prior to the bleaching area.

Mill C

Mill C has a continuous pulping process followed by brown stock washing and bleaching. The model employed for this mill does not have the washing zone simulated as a part of the digester.

The equipment considered for this section can be seen in **Table 7-1** .

  - This department includes two compact baffle filters and two thickeners.

Table 7-1: Characterization of mills A, B and C.

Mill-Line	Department	Type of washers	Quantity
A	Digester	N/A-Batch process	0
	Brown stock washing-Screeners	Compaction Baffle filter	1
		Rotary Vacuum Drum	3
		Decker	1
B-Line I	Digester	Kamyr digester wash zone	1
		Pressure diffuser	1
	Brown stock washing	Rotary vacuum washer	2
		Decker	1
		Wash Press	1
B-Line II	Digester	Kamyr digester wash zone	1
		Atmospheric diffuser -2 stage	1
	Brown stock washing	Decker	1
		Wash Press	1
C	Digester	N/A for calculation	1
	Brown stock washing	CBF	2
		Thickener	2

As explained earlier, the inlet and outlet consistency are some of the critical operating variables in washing, and these values for Mill A can be seen in **Table 7-2.**

Table 7-2: Operational conditions for mills A, B and C.

Name	Type of washer	Inlet %Cs	Outlet % Cs	Shower Flow temp.[°C]	Dissolved solids in the inlet pulp [%]	Dissolved solids in the outlet pulp[%]
A-CBF 1	CBF	3.3	18	74	13.9	12.2
A-RVD 1	RVD	3.0	12	63	10.4	8.75
A-RVD 2	RVD	1.9	12	66	5.4	4.87
A-RVD 3	RVD	2.5	12	80	1.4	1.34
A-RVD 4	RVD	1.5	15	34	0.2	**0.16**
B-I -Digester wash zone	Digester wash zone	10.3	10	90.5	8.0	6.09
B-I-Pressure diffuser	Pressure diffuser	10	10	77	4.8	2.69
B-I-RVD	RVD	1.56	8	78	1.7	1.51
B-I-RVD 2	Decker	1.55	12	84	1.2	1.10
B-I-Wash Press Delignification	Wash Press	3.4	25	71	0.3	**0.29**
B-II- Digester wash zone	Digester wash zone	9.84	10	70	19.1	11.09
B-II-Atmospheric diffuser -2 stage	Atmospheric two stage diffuser	10	10	76	3.6	2.77
B-II-RDV	RVD	1.47	8	71.5	1.1	1.01
B-II-Wash press	Wash Press	3.5	30	68	0.5	**0.46**
C-CBF 1	CBF	2.8	13	52	6.1	3.6
C-CBF 2	CBF	4.67	13	37	1.4	0.92
C-RVD 1	RDV	0.7	14	52	0.0	0.036
C-RVD 2	RDV	0.7	14	52	0.0	**0.036**

The values in blue represent the dissolved solids at the outlet of the last brown stock washer, as it can be observed mill C delivers a very clean pulp in comparison with mill A and B. Also can be observed that mill B uses shower flow temperature in the range of 68°C -90.5°C. Mill A and B wash pulp in one equipment with shower flow temperatures 34°C - 37 °C respectively.

7.1.2 Key Performance Indicators for brown stock washing

In this section of the analysis performance indicators were calculated, including displacement ratio, (DR), dilution factor, (DF), equivalent displacement ratio, (EDR), Modified Norden Efficiency Factor (E_{st}), percentage total washing efficiency and the percentage of solids removed from the pulp for all three mills.

Table 7-3: Key Performance Indicators

Washer name	**Displacement Ratio, (DR)**	**Dilution Factor, (DF)**	**Equivalent displacement ratio, (EDR)**	**Modified Norden efficiency E_{10}**	**% Yield**
A-CBF 1	0.77	4.54	**0.83**	3.7	88%
A-RVD 1	0.64	0.26	**0.61**	2.5	84%
A-RVD 2	0.70	0.60	**0.69**	3.0	91%
A-RVD 3	0.70	0.62	**0.76**	3.7	96%
A-RVD 4	0.60	-1.00	**0.69**	3.9	97%
B-I -Digester wash zone	0.93	3.56	**0.87**	5.2	76%
B-I-Pressure diffuser	0.83	3.71	**0.68**	2.6	56%
B-I-RVD	0.74	4.33	**0.57**	2.6	87%
B-I-RVD 2	0.80	3.58	**0.79**	3.6	91%
B-I-Wash Press Delignification	0.65	2.58	**0.84**	4.6	96%
B-II- Digester wash zone	0.82	1.08	**0.73**	4.0	58%
B-II-Atmospheric diffuser -2 stage	0.89	3.15	**0.88**	3.6	76%
B-II-RDV	0.73	1.49	**0.57**	1.8	90%
B-II-Wash press	0.70	4.52	**0.89**	3.1	97%
C-CBF 1	0.81	1.27	**0.82**	8.2	59%
C-CBF 2	0.70	-0.88	**0.71**	-4.6	66%
C-RVD 1	0.83	6.72	**0.86**	5.1	80%
C-RVD 2	0.83	6.72	**0.86**	5.1	80%

N/A means that the value is out of the crossing point of Modified Norden Efficiency factor and dilution factor

In the table can be observed the values in red mean out of the typical range for EDR . In the case of the percentage washing efficiency it is noticed that for some equipments the parameter could not be obtained, when it was obtained it was benchmarked but just for two types of washer, rotary vacuum drum and wash press. For the washer B-I-RVD for the EDR it equipment is operating below the typical range and for the percentage washing efficiency it is operating above the washing efficiency.

7.1.3 Benchmarking against typical values and diagnosis

A benchmarking of the washer performance of each mill was compared against typical values of the equivalent displacement ratio (EDR). KPI indicators, such as the percentage of total washing efficiency and dissolved solids removal, were also calculated, but a percentage of washing efficiency benchmarking could only be done for the rotary vacuum drum and wash presses due to limited literature data.

The percentage of dissolved solids removal was calculated, and although this parameter is not widely used in literature, it was used in this work as an extra parameter to confirm that the EDR and percentage total washing efficiency both have the same trend as the percentage of dissolved solids removal.

The drawback of the Modified Norden efficiency (E_{st}) is that this parameter can be used only when the operational shower flow permits a DF equal to 2.5, and is rare to use as a washing performance indicator in the normal operation of the mills.

Benchmarking

Mill A

The benchmarking for all the washers shows that the performance values that are within, and in several cases, exceeding the typical value for each type of equipment, which can be seen in **Figure 7-1.**

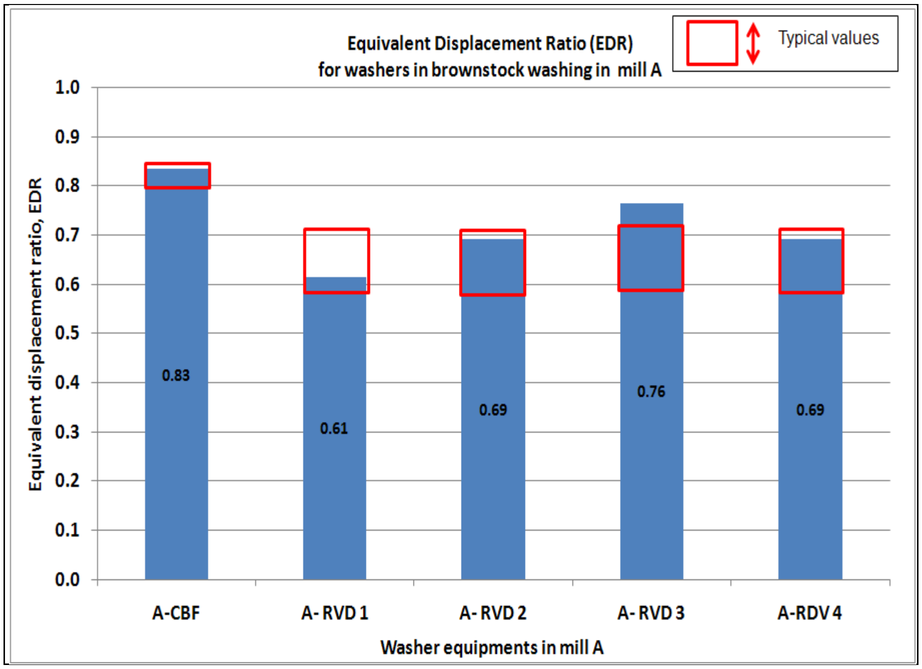

Figure 7-1: EDR for mill A.

Mill B-Line I

The washing performance indicators are not within the range except for the decker, called in A-RDV-2.

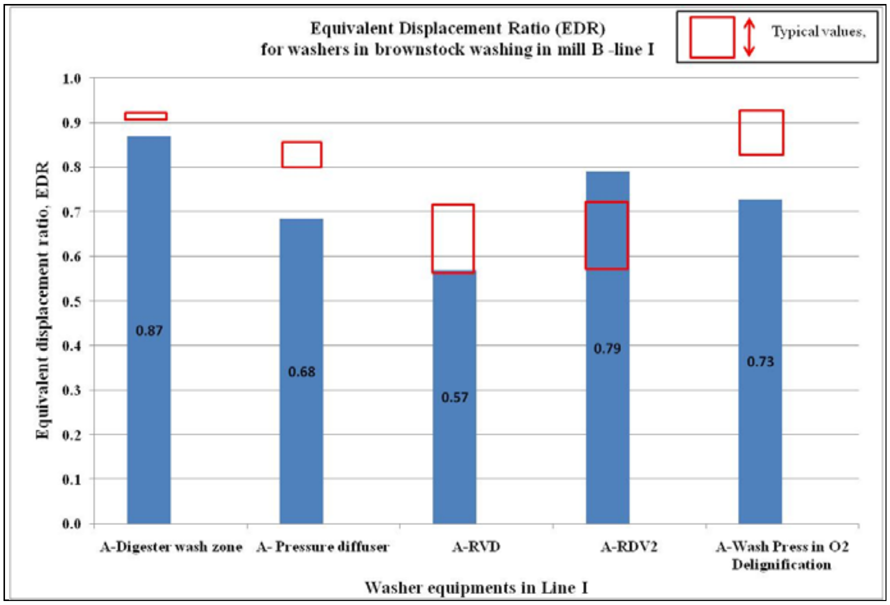

Figure 7-2: EDR for mill B line I.

Mill B-Line II

The washing performance indicators for the washers in line II area are out of the range, except for the B-II-wash press.

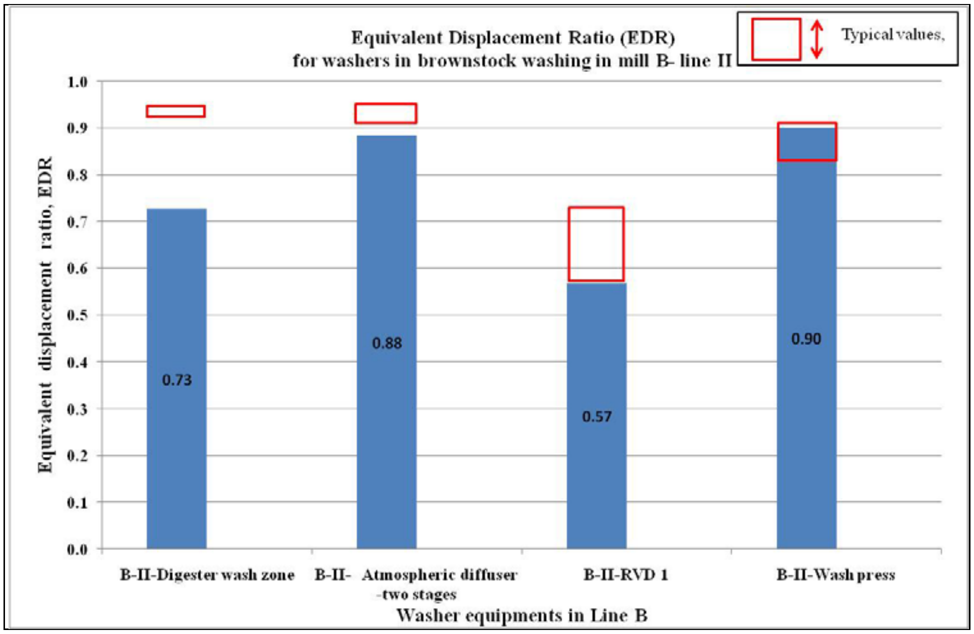

Figure 7-3: EDR for mill B line II.

Mill C

The EDR as washing performance indicators for the washers in mill C are presented in **Figure 7-4** and they are compared with the accepted range of operation. All washers are working within the range of EDR according to their type of washer, except for C-CBF2

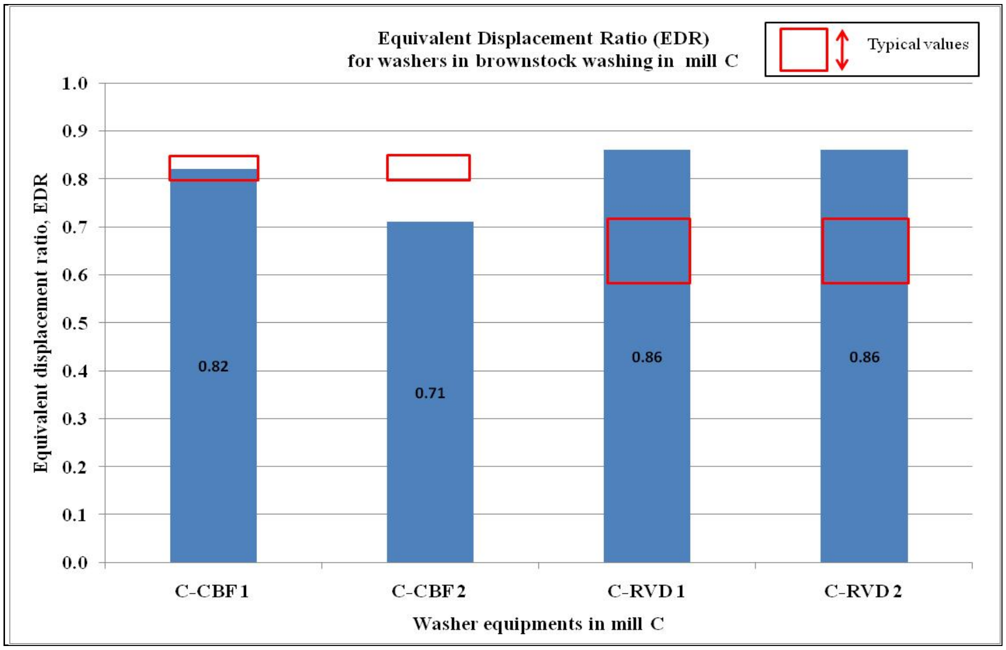

Figure 7-4: EDR for mill C.

Diagnosis

In Table 7-4 is presented the specification of displacement ratio, (DR) for each mill. In the second column the equivalent displacement ratio, (EDR) is calculated with equation 29. The variables needed to evaluate equation 29 are DR, that is specified, discharge correction factor, (DCF), and inlet correction factor , (ICF). The equation to calculate the DCF is the equation 30, which depends on the discharge consistency, (C_d), and the inlet correction factor, (ICF). which is evaluated with the equation 31, and depends on the dilution factor, DF, and discharge consistency, (C_d),

One of the steps is to verify if the DR specified in the simulation model, when it is converted to EDR, is within the range of EDR for the selected equipment, then evaluate if the operation conditions are appropriate to obtain a calculated EDR within the typical range for the selected equipment.

Table 7-4: Key Performance Indicators for mills A, B and C

Name	**DR** Specified in Cadsim Plus ®	**EDR** obtained from eq. 10	**Typical EDR**	**EDR calculated**
A-CBF 1	0.70	0.80	0.80-0.85	0.83
A-RVD 1	0.72	0.72	0.58-0.72	0.63
A-RVD 2	0.72	0.72	0.58-0.72	0.65
A-RVD 3	0.72	0.72	0.58-0.72	0.72
A-RVD 4	0.60	0.69	0.58-0.72	0.69
B-I -Digester wash zone	0.89	0.80	0.93	0.87
B-I-Pressure diffuser	0.845	0.70	0.80 - 0.85	0.68
B-I-RVD	0.7	0.70	0.58-0.72	0.57
B-I-RVD 2	0.7	0.69	0.58-0.72	0.79
B-I-Wash Press Delignification	0.77	0.77	0.83-0.92	0.90
B-II- Digester wash zone	0.82	0.85	0.93	0.71
B-II-Atmospheric diffuser -2 stage	0.72	0.84	0.92-0.96	0.77
B-II-RDV	0.65	0.43	0.58-0.72	0.57
B-II-Wash press	0.68	0.88	0.83-0.92	0.90
C-CBF 1	0.85	0.85	0.80-0.85	0.81
C-CBF 2	0.85	0.85	0.80-0.85	0.71
C-RVD 1	0.7	0.75	0.58-0.72	0.86
C-RVD 2	0.7	0.75	0.58-0.72	0.86

In **Table 7-4** it can be observed that some specifications for the equipment were higher than the typical value or lower than the typical EDR. That equipment where the specification was out of the range is colored in red. It was found that mill B had specified some equipment with lower DR and EDRs, and for mill C two pieces of equipment were specified with a higher DR, and EDRs. It will be presented in a diagnosis of all equipment for the three mills.

Mill A

For the washer A-CBF-1, the calculated EDR is in the range and because the shower flow allowed a DF of 4.5, which is higher than the recommended value of 2.5, the final EDR calculated is 0.83. The inlet and outlet consistency were 3.3 and 18%, which is within the recommended range for this type of washer.

For washer A-RVD 1 the specified EDR is in the range (0.58- 0.72), the DF is 0.26, which is a low value, but the fact that the typical EDR value specified is the highest of the typical range and the inlet and outlet consistency are 3% and 12% (typical outlet consistency 12%) the calculated EDR is 0.63, which is within the range.

For washer A-RVD 2, the specified EDR is in the range (0.58- 0.72) , the DF is 0.60, which is a low value , but the fact that the typical EDR value specified is the highest and the inlet and outlet consistency are 1.9% and 12% (typical outlet consistency 12%,) the calculated EDR is 0.65, which is within the range.

For washer A-RVD 3, the specified EDR is in the range (0.58- 0.72), the DF is 0.62, which is a low value, but the fact that the typical EDR value specified is the highest of the typical range, and the inlet and outlet consistencies are 1.9% and 12% (typical outlet consistency 12%,) the calculated EDR is 0.72, which is in the upper level of the range.

For washer A-RVD 4, the specified EDR is in the range (0.58- 0.72), the DF is -1.00, which is a very low value, but the fact that the typical EDR value specified is the highest of the typical range and the inlet and outlet consistencies are 1.5% and 15% (typical outlet consistency 12%) the calculated EDR is 0.69, which is within the range.

According to the analysis all the washers for mill A are working within the typical values, for the type of equipments that are used.

Mill B

For the wash zone of the continuous digester of mill B, called in this project as B-I - Digester wash zone, a DR of 0.89, which is low for the type of equipment according to Poulin (2005). The DF that the equipment presented is 3.56 and inlet and outlet consistencies are the same 10% Cs, consistencies that are normal for this type of equipment. The typical EDR obtained from equation 10 is 0.85. The calculated EDR according to the previous operational conditions is 0.87, concluding that the digester wash zone is working below the typical value.

For the equipment B-I-Pressure diffuser an EDR lower than the typical value was specified, indirectly. The inlet and outlet consistencies are 10%, which are normal values for pressure diffuser. A DF of 3.56 was computed, as a result the EDR computed is 0.68, which is below the typical range for this type of equipment. It can be improved specifying a value of EDR in the simulation.

For the rotary drum, B-I-RVD 1, a DR of 0.7 was specified in the simulation. The inlet and outlet consistencies are 1.56% and 8%, where the outlet consistency is below the typical value for rotary vacuum drums, which is 12% approximately. Df value of 4.33 and EDR of 0.57 are calculated and they are slightly below the lower value of the typical range, due to a low outlet consistency. Low consistencies in the outlets are caused by a loss of vacuum, a problem that can be solved by changing the drum

For the decker, B-I- RVD 2, a DR of 0.7 was specified in the simulation. The inlet and outlet consistencies are 1.50% and 12%, where the outlet consistency is normal for rotary vacuum drums and deckers, which is 12% approximately. A DF of 3.58 was computed; as a result the EDR computed is 0.79, which is slightly higher than the upper value of the typical range, due to a DF greater than the typical.

For the wash press, B-I-Wash Press Delignification, the inlet and outlet consistencies are 3.4% and 25%, where the typical outlet consistency is in a range of 25-32 %. A DF of 2.58 was computed; as a result the EDR computed is 0.90, which is within the typical range (0.83- 0.92).

For the B-II- Digester wash zone, the DF that the equipment presented is 1.08 and inlet and outlet consistencies are the same 10% Cs, consistencies that are normal for this type of equipment. The typical EDR obtained from equation 10 starting from the typical value of DR is 0.85. The calculated EDR according to the previous operational conditions is 0.71, concluding that the digester wash zone is working below the lower level of the typical range. One of the reasons is the specified DR in the model, and also a low DF compared to the typical value of 2.5. For the two stage atmospheric diffuser a DR of 0.74 was specified for each stage, giving a total DR of 0.84 , which corresponds to an EDR of 0.77 and the typical value for this equipment is in the range of (0.92- 0.96). The inlet and outlet consistencies are 10%, which are normal values for the atmospheric diffuser. A DF of 3.15 was computed and as a result the EDR computed is 0.88, which is a bit below the lower value of the typical range, due to a low value of DR in the specification of DR of 0.74 that corresponds to an EDR of 0.77.

For the rotary drum, B- RVD1, a DR of 0.65 was specified. The inlet and outlet consistencies are 1.56% and 8%, where the outlet consistency is below the typical value for rotary vacuum drums, which is 12% approximately. A DF of 1.5 was computed; as a result the EDR computed is 0.57, which is slightly below the lower value of the typical range, due to a low outlet consistency and low DF and DR in the specification. For this mill it was recommended to change the rewetting, due to the low outlet consistency, which affects the washing.

For the wash press, B-wash press a DR of 0.68 was specified. The inlet and outlet consistencies are 3.4% and 30%, where the normal outlet consistency for a wash presser is in the range of 25-32%. A DF of 4.53 was computed; as a result the EDR computed is 0.90, which is within the typical range, which is 0.83- 0.92.

Mill C

For the washer C-CBF 1, the specified EDR is in the range for this type of washer, which is (0.80 -0.85). The shower flow allowed a DF of 1.27, which is a bit lower than the recommended value of approximately 2.5. The inlet and outlet consistencies were 2.8 and 13%, where the outlet consistency is a bit below the typical values (14% -18%). The final EDR calculated is 0.81, which is within the range, mainly because the specification for the equipment was set with the higher value of the range, even the DF and outlet consistency were slightly below the typical values.

For the washer C-CBF 2, like the C-CBF1, the value is within the typical range of values. The DF obtained due the operational conditions is -0.88, which is way below the typical value of 2.5. The inlet and outlet consistencies are 4.67% and 13%, which for the inlet is a bit higher than expected for CBF’s, which is around 3.5% and the outlet consistency is slightly below the typical value of 14% - 18%. As a result an EDR of 0.71 was obtained a value below the lower range of the typical values and this is related to several variables, such as high inlet consistency, lower outlet consistency, and low DF.

The thickeners, commonly called by this name in the mills, correspond to the rotary vacuum drum where the pulp was split into C- RVD1 and C-RVD2, where a DR of 0.7 corresponds to an EDR of 0.75 for each washer, which is a value slightly above the upper value for the range (0.58-0.72). The inlet and outlet consistencies are 0.7% and 14%, where the outlet consistency is a bit over the typical value for rotary vacuum drums, which is 12% approximately. A DF of 6.72 was computed, which is extremely high compared to the typical value of 2.5. As a result of a high outlet consistency, a slightly higher DR value is specified for the equipment and a very high value of DF, therefore an EDR of 0.86 is obtained.

7.2 Energy and water projects proposal to enhance washing performance

Energy and water saving projects are proposed for the three mills in proposed projects.

Table 7-5 .These projects are mainly water saving projects, with an effect on steam savings. First, the base case configuration for each case study mill is presented and then water and steam saving projects are presented. As for base case for each mill, the configuration of washing, bleaching, and evaporation departments are presented. Although this study is more focused on the brown stock washing section, the impact of changes are illustrated in bleaching and evaporation department. Moreover, steam and water consumption for base case configuration are presented for further comparison with the proposed projects.

Table 7-5: Projects for mills A, B, and C.

Name	**Description**
Project A-1	Fresh water elimination and chemical heating
Project A-2	Rotary vacuum drum replacement with wash press
Project B-I-1	Increment of outlet consistency in rotary vacuum drum.
Project B-I-2	Increment of outlet consistency of a rotary vacuum drum and the wash press
Project B-I-3	Increment of outlet consistency of a rotary vacuum drum and the wash press and addition of a rotary vacuum drum.
Project C-1	FW replacement with white water, control HW and bleaching filtrates to DF of 2.5, HW control of HW to sealed tank with temperature
Project C-2	Includes the project C-1, and CBF consistency increment, HW replacement in bleaching, and in CBF with white water

7.2.1 Water and energy saving projects - Mill A

Base Case

In **Figure 7-5** the base case configuration for mill A, which represents the current situation of the mill, is presented. The connection between the brown stock washing section and the bleaching and evaporation sections is well illustrated. Changing water consumption in the brown stock section benefits the overall mill regarding fresh water consumption in general. However, decreasing water consumption has a direct effect on chemical consumption in the bleaching section due to dirtier pulp, but it decreases the steam consumption in the evaporation section due to increasing the dissolved solid concentration of black liquor. Thus, any changes in steam and water consumption in the previous departments along with dissolved solid concentration in pulp are the indicators that are investigated. **Table 6.-6** presents these indicators for the base case.

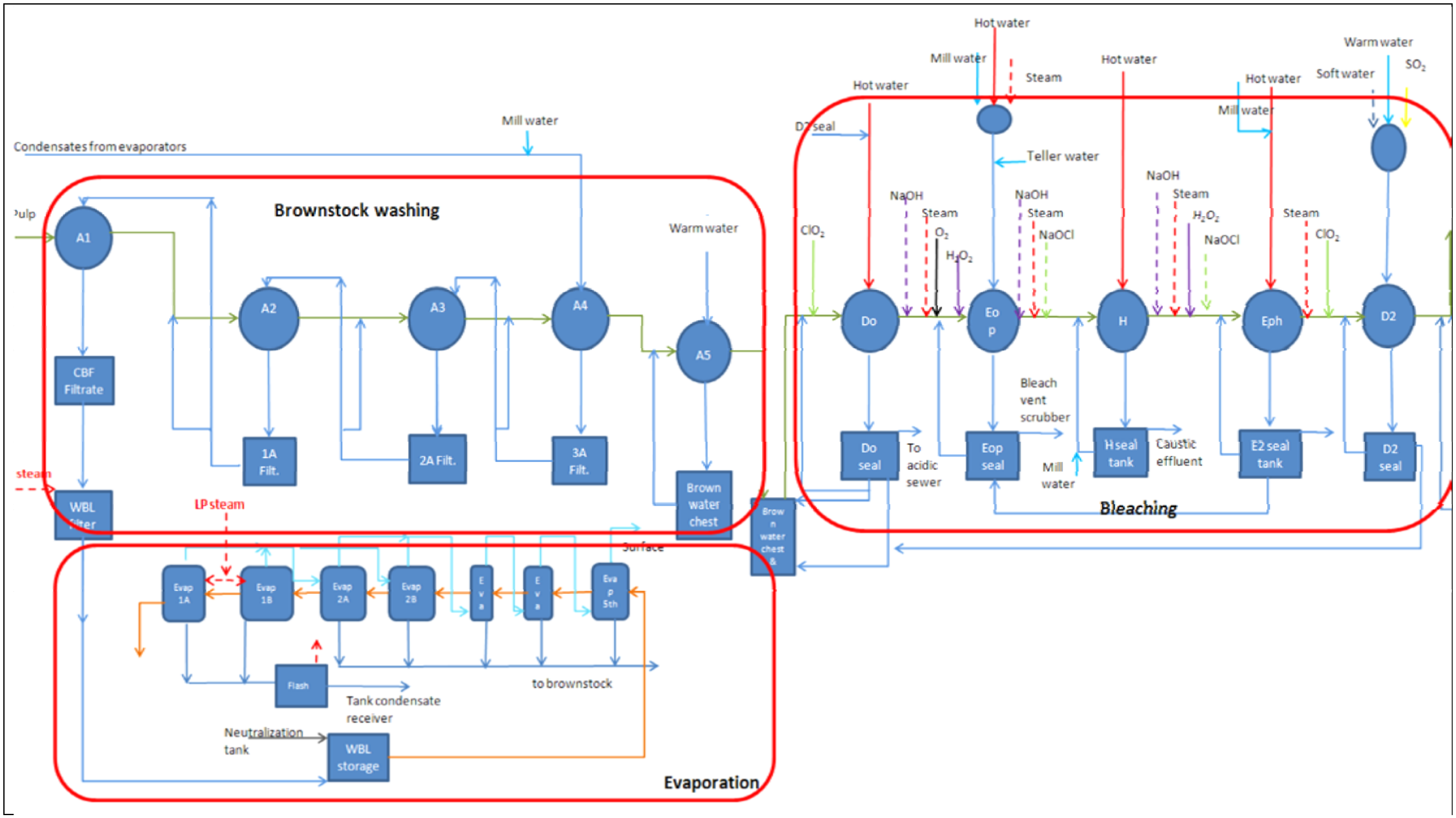

Figure 7-5: Mill A Base Case

Table 7-6: Mill A Base Case-Water and Steam Consumptions, and Ds% in Pulp .

Section	Water Consump. [m^3/bdt]	Steam Consump. [GJ/adt]	DS out in pulp %
Brownstock	10.1	N/A	0.16
Bleaching	23.5	2.39	---
Evaporator	N/A	3.75	N/A
Rest of the process	54.4	22.06	---
Total	88	28.2	---

Project A-1: Fresh water elimination and chemicals heating

The first project for mill A is the elimination of fresh water, which mixes with evaporator condensate. This water is used to decrease the temperature of the evaporator condensates from 95°C to 80°C. The decrement in the temperature is due to the possible flash of the water resulting from the vacuum ejected in the rotary vacuum drums (RVD's). If the fresh water is eliminated then the heat should be removed from condensate and transferred to the process to avoid flash in pulp line. The heat removed from the condensates is 2.4 MW and is used to heat up chemicals used in bleaching section. NaOH is heated from 15°C to 75°C and the remaining heat (0.163MW) is exchanged with fresh water used in the bleaching section to heat it up to 75°C. The last part of the proposed project is the replacement of fresh water in the sealed tank with white water. A detailed explanation for each sub-project is given in figures **Figure 7-6** to **Figure 7-9** and the summary of the impact of implementing all the aforementioned projects is presented in **Table 7-7**. In terms of results, a 3.3% reduction in water and a 1.8% savings in steam are achieved by applying project A-1 inclusively.

1.1 Fresh water elimination

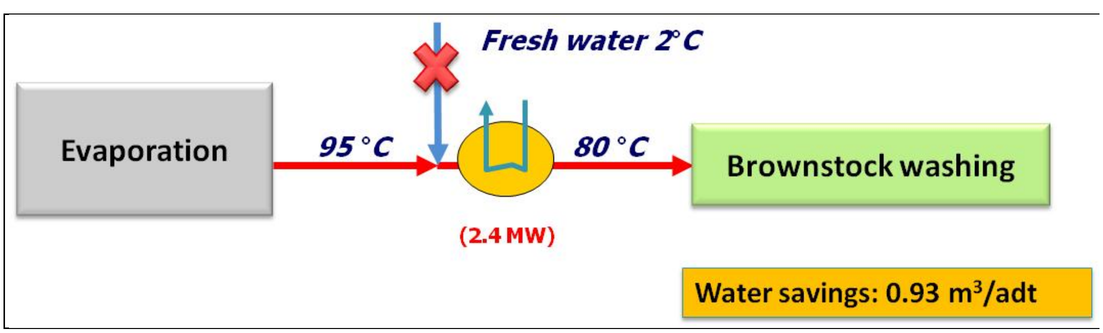

Figure 7-6: Sub-project 1.1 of the project A-1

In the sub project 1.1 heat is removed from the evaporator condensates in order to keep the temperature at 80°C, the temperature constraint for the rotary vacuum drum. Due to the vacuum in the equipment, the flash points occur around 80°C. In this sub-project 2.4 MW are available for the process.

1.2 Heating chemicals

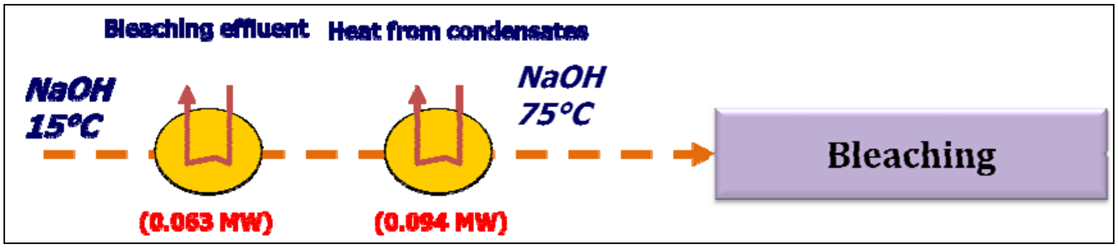

Figure 7-7: Sub-project 1.2 of the project A-1

The sub-project 1.2 is based on the possibility of heating up NaOH from 15°C to 75°C, using two heat sources, bleaching effluents and the heat from condensates as can be seen in **Figure 7-7**. Up to this point 2.3 MW are available from the evaporator condensates.

1.3 Fresh water heating

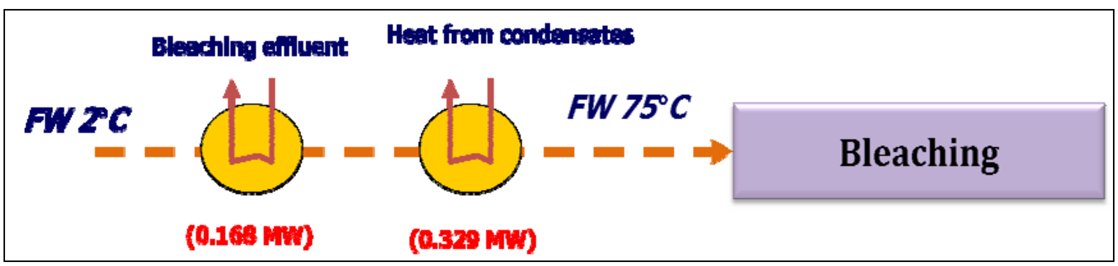

Figure 7-8: Sub-project 1.3 of the project A-1

The sub-project 1.3 is based on the possibility of heating up fresh water from 2°C to 75°C, using two heat sources, bleaching effluents and the heat from condensates as can be seen in **Figure 7-8**Up to this point 1.95 MW are available from the evaporator condensates.

1.4 Fresh water heating

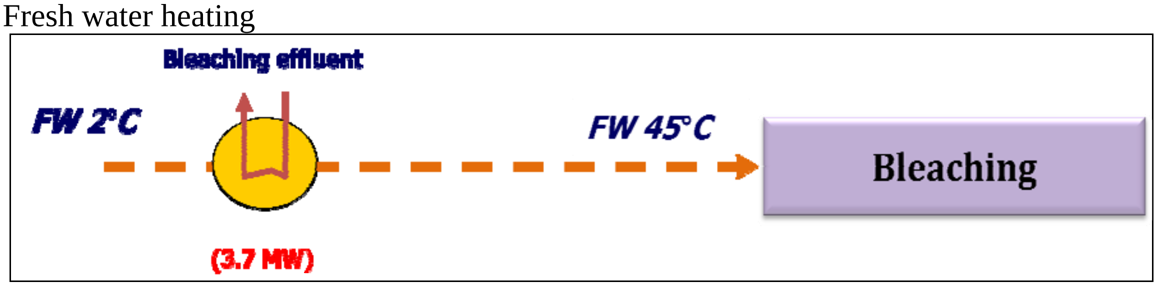

Figure 7-9: Sub-project 1.4 of the project A-1

The sub-project 1.4 is based on the possibility of heating up fresh water from 2°C to 45°C, using bleaching effluents as can be seen in **Figure 7-9**. Up to this point 1.95 MW are available from the evaporator condensates.

1.5 Fresh water in sealed tank replacement with white water

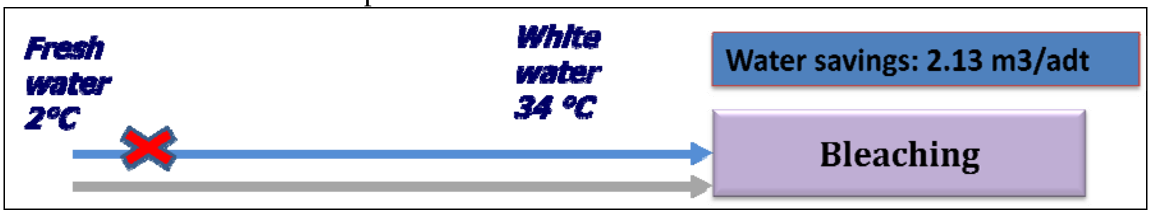

Figure 7-10: Sub-project 1.5 of the project A-1

The sub-project 1.5 is based on the possibility of replacing fresh water from 2°C with white water from the pulp machine in bleaching, saving 2.13 m^3/adt as can be seen in **Figure 7-10**, and the 1.95 MW of heat that was not used can be given to other areas of the Kraft process.

Table 7-7: Project A-1Water and Steam consumptions, and Ds% in pulp.

Section	**Water Consump. [m^3/adt]**	**Steam Consump. [GJ/adt]**	**DS out in pulp %**
Brown stock	9.2	-----	**0.350**
Bleaching	21.3	2.22	-----
Evaporator	-----	3.72	-----
To Process	57.5	-0.29	-----
Total	84.9	27.06	-----

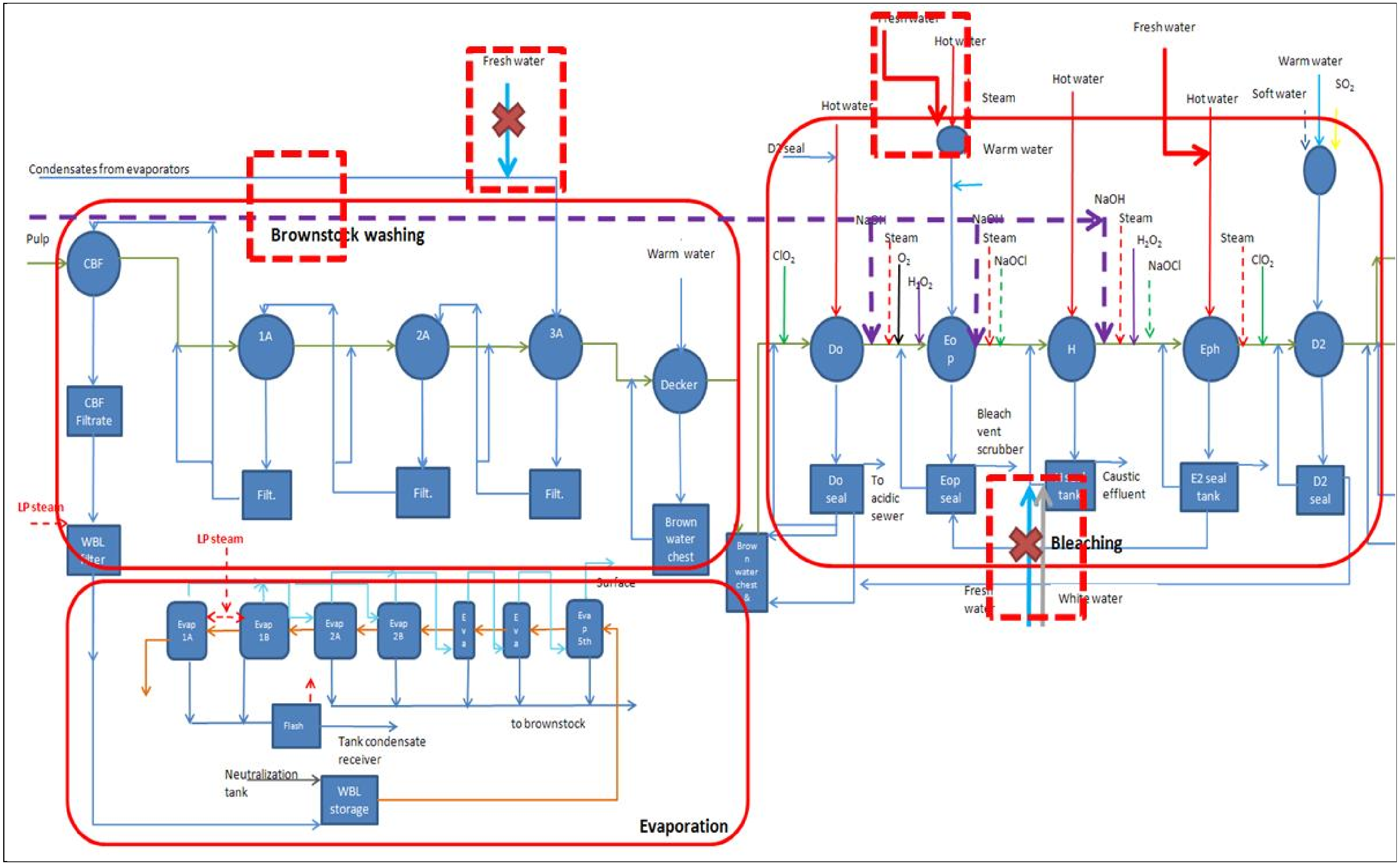

Figure 7-11: Mill A Project A-1.

Project A-2: Rotary Vacuum drum replacement with wash press

Project A-2 includes the subprojects in project A-1 and the replacement of the mill's three rotary vacuum drums (RVD) with a high efficiency washer as the wash press. The main characteristic of the wash press is that the outlet consistency of the pulp is increased from 25% to 32%, which allows a dilution factor of 2.5 with less shower flow. The project is composed of the same subprojects as project A-1, and the replacement of the three rotary vacuum drums for a wash press. The base case washers and the replacement with the wash press is presented in **Figure 7-11** and in **Figure 7-12**. **Table 7-8** shows the water and steam consumption in the mill after applying the projects in the simulation. The water and steam savings are 3.4% and 1.8%, respectively. Just applying the project A-2, the savings in projects A-1 and A-2 cannot be added. The advantage of project A-2 is in discharging a cleaner pulp for the subsequent bleaching stage, which results in less chemical consumption.

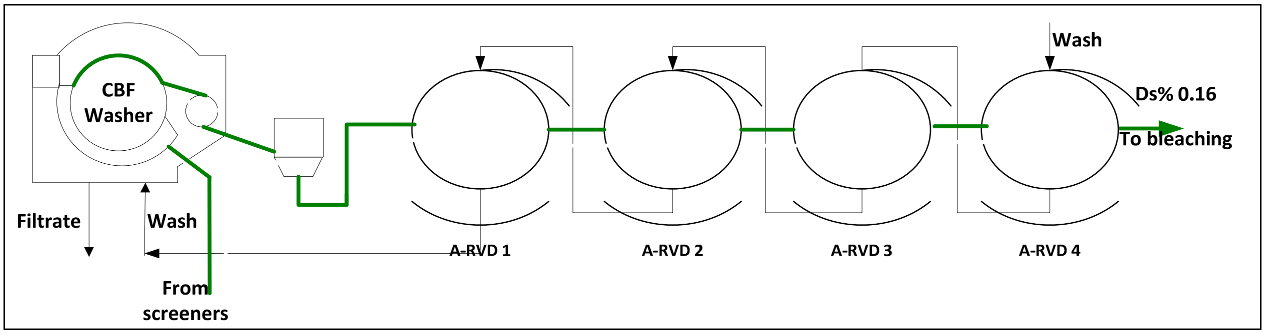

Figure 7-12: Simplified diagram of mill A base case.

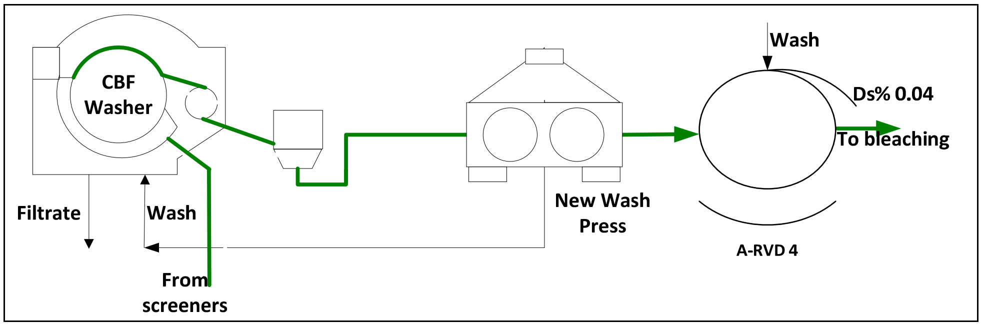

Figure 7-13: Simplified diagram of mill A project A-2

Table 7-8: Project A-2 Water and Steam consumptions, and Ds% in pulp.

Section	**Water Consump. [m^3/adt]**	**Steam Consump. [t/adt]**	**DS out in pulp %**
Brown stock	8.9	----- -----	0.04
Bleaching	21.5	2.20	0.035
Evaporator	-----	3.72	-----
To Process	-----	-0.29	-----
Rest of deparment	54.4	21.4	
Total	84.8	27.04	-----

The main difference between projects A-1 and A-2 is in the quality of the pulp. In the base case, the concentration of dissolved solids was 0.16%, with project A-1 increasing this to 0.35% but in project A-2, the pulp had a very low concentration of dissolved solids (0.04%) with respect to dissolved solids concentration in the base case. If the mill is satisfied with the quality of the pulp in the base case, more savings in water and energy can be achieved. In project A-2 chemical consumption is expected to decrease, but it is not possible to quantify due to limitations in the correlation of chemicals and dissolved solids.

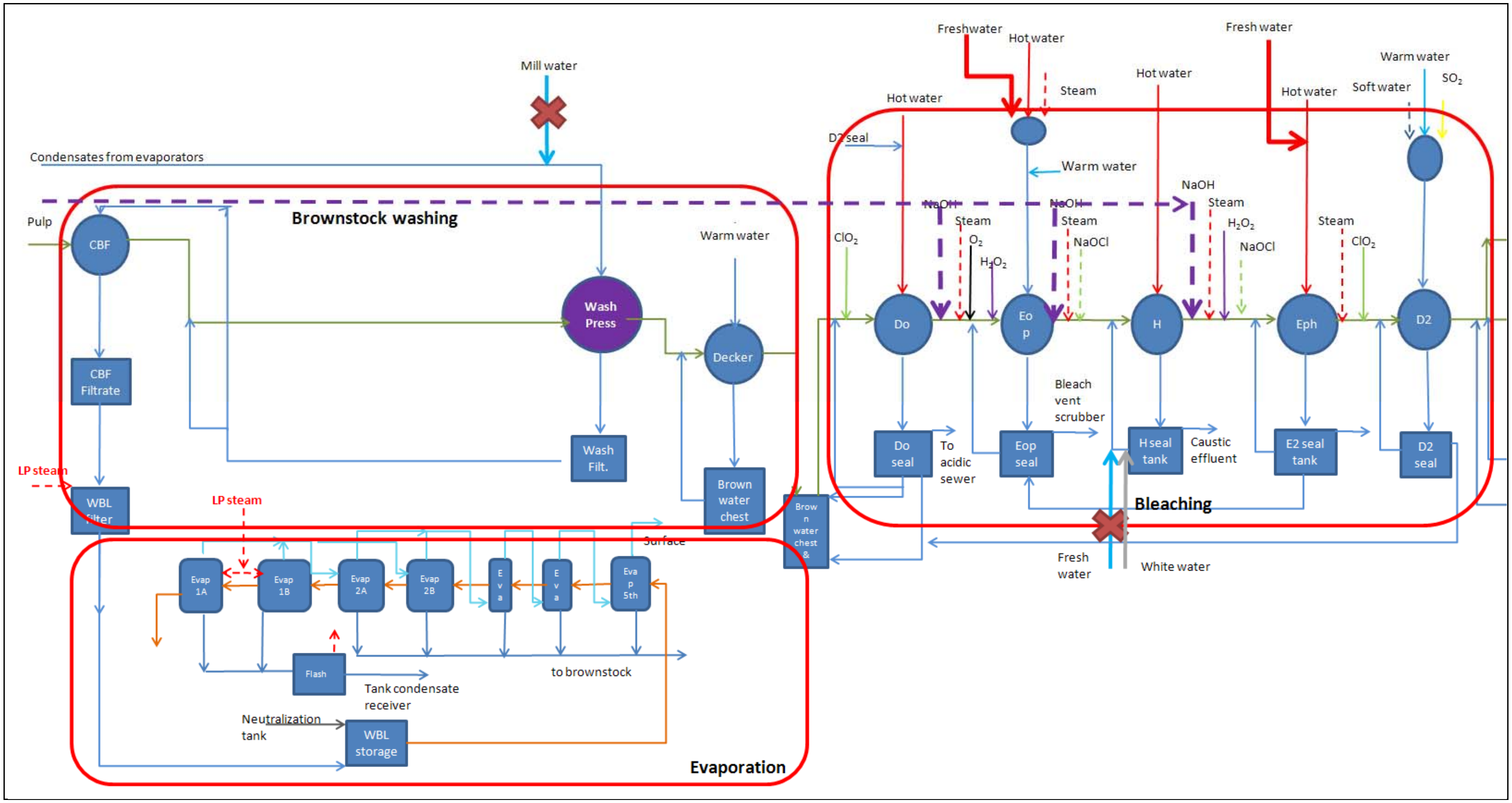

Figure 7-14: Mill A Project A-2

7.2.2 Water and energy saving projects - Mill B

Mill B- Base case

As mentioned earlier, mill B has two parallel production lines. The base case is presented in **Figure 7-15**, which shows the simplified base case configuration for brown stock washing in line I. The projects in line II are not presented here because of the similarity with the type of projects applied in line I. The value for water consumption, energy consumption and dissolved solids in the washed pulp are shown in **Table 7-9**.

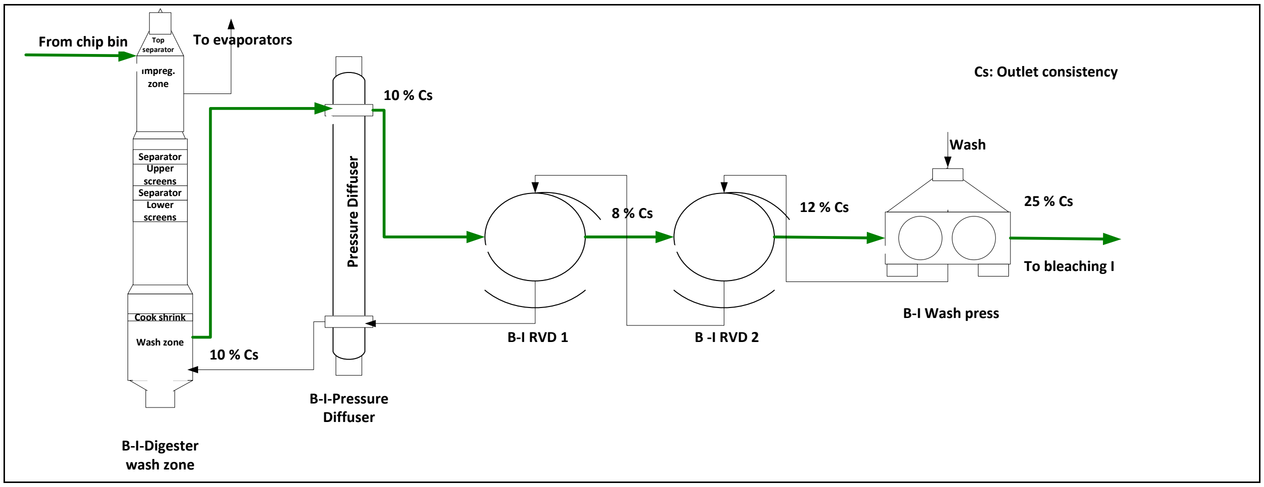

Figure 7-15: Simplified diagram of mill B base case.

Table 7-9: Mill B base case water and steam consumptions, and Ds% in pulp.

Section	**Water Consump. [m^3/adt]**	**Steam Consump. [GJ/adt]**	**DS out in pulp [%]**
Brown stock	3.85	----- -----	0.42
Bleaching	25.3	5.15	-----
Evaporator	-----	1.76	-----
Rest of the process	18.25	9.56	
Total	47.4	16.47	-----

Project B I-1 Increment of outlet consistency in a rotary vacuum drum

The outlet consistency of the rotary vacuum drum in line I is 8%, which is very low for this type of washer. According to washer suppliers and Tuner (2001) the problem can be solved by replacing the drum, which is relatively cheaper than changing the equipment. The implementation of this project in the simulation reduced the water consumption by 1.0% and steam by 0.3%. **Table 7-10** summarizes the water, steam, and dissolved solids after applying the project.

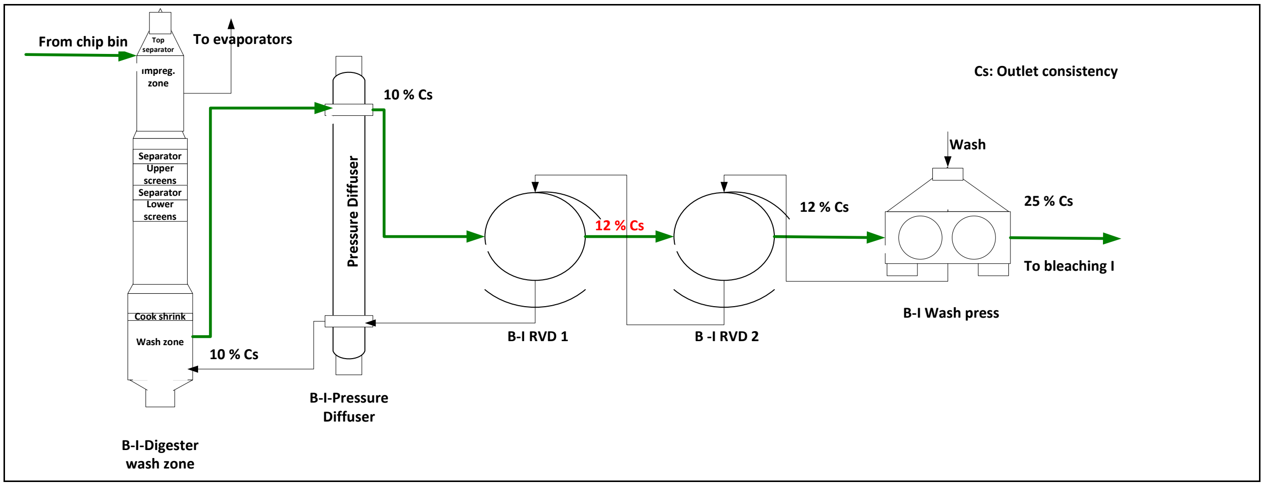

Figure 7-16: Simplified diagram of mill B project B-I-1.

Table 7-10: Project B-I-1, water and steam consumptions, and Ds% in pulp.

Section	**Water Consump. [m³/adt]**	**Steam Consump. [GJ/adt]**	**DS out in pulp [%]**
Brown stock	3.05	-----	0.42
Bleaching	25.3	5.14	----
Evaporator	-----	1.75	-----
Rest of the process	18.25	9.56	
Total	46.6	16.45	-----

Project B I-2: Includes project B-I1, an increment of outlet consistency, and the wash press

This project is proposed to increase outlet consistency of the wash press washer to 30%. This proposition produces a cleaner pulp and a decrement in the shower flow, to keep the same dissolved solids concentration at the outlet of the washer as highlighted in **Figure 7-17**.

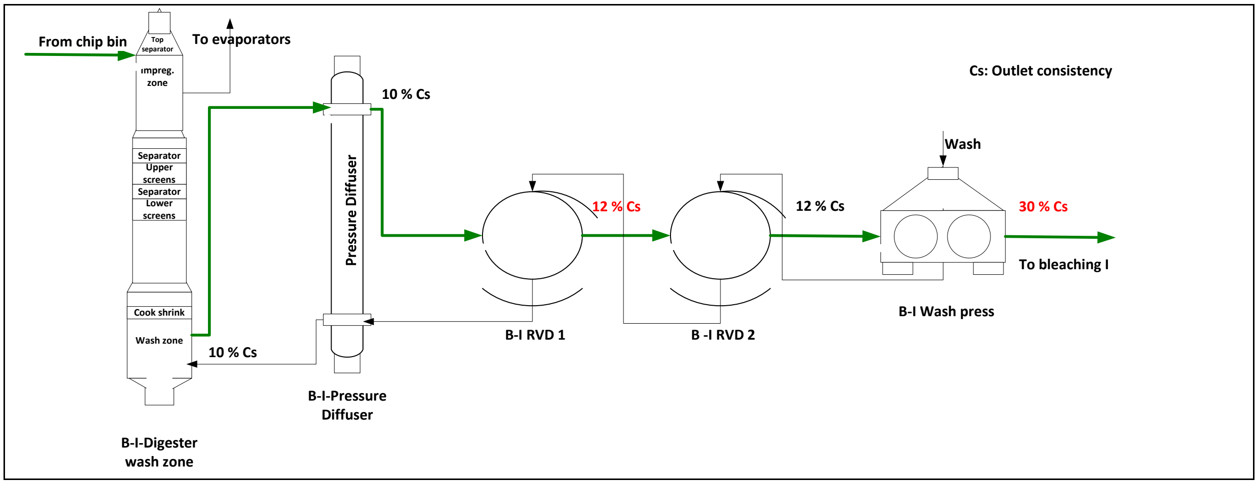

Figure 7-17: Simplified diagram of mill B project B-I-2.

The implementation of this project results in a water savings of 1.9% and steam savings of 0.5% in the mill. **Table 7-11** presents water and steam savings.

Table 7-11: Project B- I - 2 water and steam consumptions, and Ds% in pulp.

Section	Water Consump. [m^3/adt]	Steam Consump. [GJ/adt]	DS out in pulp [%]
Brown stock	2.0	-----	0.42
Bleaching	25.1	5.13	----
Evaporator	-----	1.76	-----
Rest of the process	18.25	9.56	
Total	45.35	16.45	-----

Project B I-3: Includes project B I-2 and the addition of a rotary vacuum drum.

Adding a new washer to the set of existing washers in the mill decreases the dissolved solids concentration, Ds% in the pulp. In this project the addition of the same type of the washer is done to reduce the shower flow in the last washer as the shower flow is controlled by the Ds%.

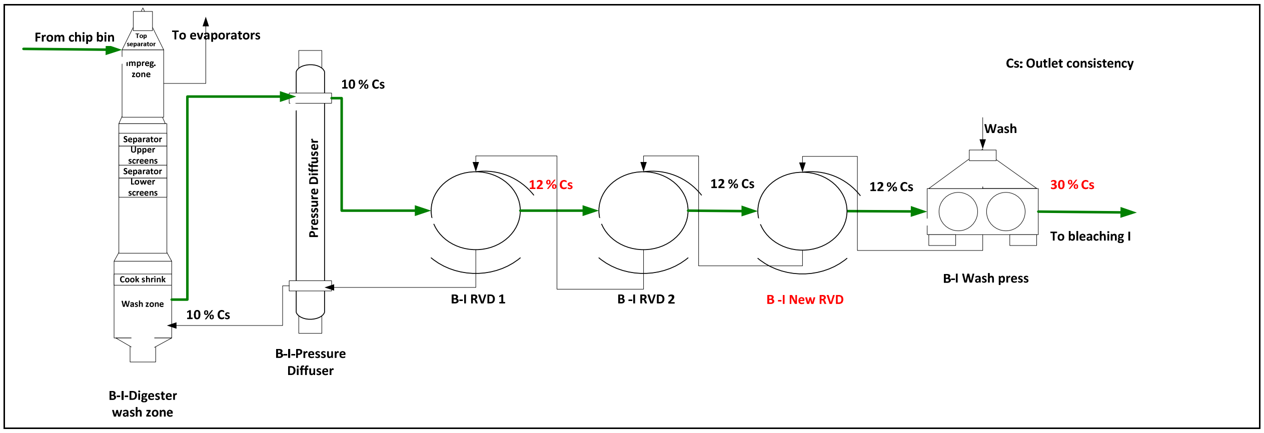

Figure 7-18: Simplified diagram of mill B project B-I-3.

By applying this project in the simulation a reduction in the water supply of 4.3% and a decrement in the steam demand of 1.6% were observed. **Table 7-12** presents water and steam savings.

Table 7-12: Project B- I - 2 water and steam consumptions, and Ds% in pulp.

Section	**Water Consump. [m^3/adt]**	**Steam Consump. [GJ/adt]**	**DS out in pulp [%]**
Brown stock	3.05	-----	0.42
Bleaching	25.3	1.74	----
Evaporator	-----	4.52	----
To rest of the process	16.05	9.94	----
Total	45.1	16.2	----

The main difference between projects B-I-1, B-I-2, and B-I-3 is that project B-I-2 includes the savings of project B-I-1 and other subprojects and the same for project B-I-3. Basically, the projects in mill B are based on the improvement of the operational conditions in the washers, by means of replacing some part of the equipment, which allows the equipment to perform better while keeping the same quality in the product.

7.2.3 Water and energy saving projects - Mill C

Mill C-Base case

The base case for mill C consists of four washers. They are C-CBF 1 and 2, and C-RVD 1 and 2. Washers C-RVD 1 and 2 use fresh water at 2°C in the wire cleaning. There are other streams, such as water and wash liquor from the subsequent stage of bleaching entering the washers that results in a DF of 6.72. Basically, the flow of these streams is fixed values in simulation as the values are validated by mill personnel. Moreover, there is a fixed flow of hot water to the filtrate sealed tank to keep the filtrate temperature (black liquor) at 36°C. This hot water mixing in the tank results in a huge overflow of 415 m^3/h.

For washers C-CBF1 and C-CBF-2 there are some important aspects to point out, such as how water and evaporator condensates are used for wire cleaning and the rest is sent to sewer. The outlet consistency of the C-CBF is 13%, a value slightly lower than the typical outlet consistency of the CBF's. Figure 18 shows the base case.

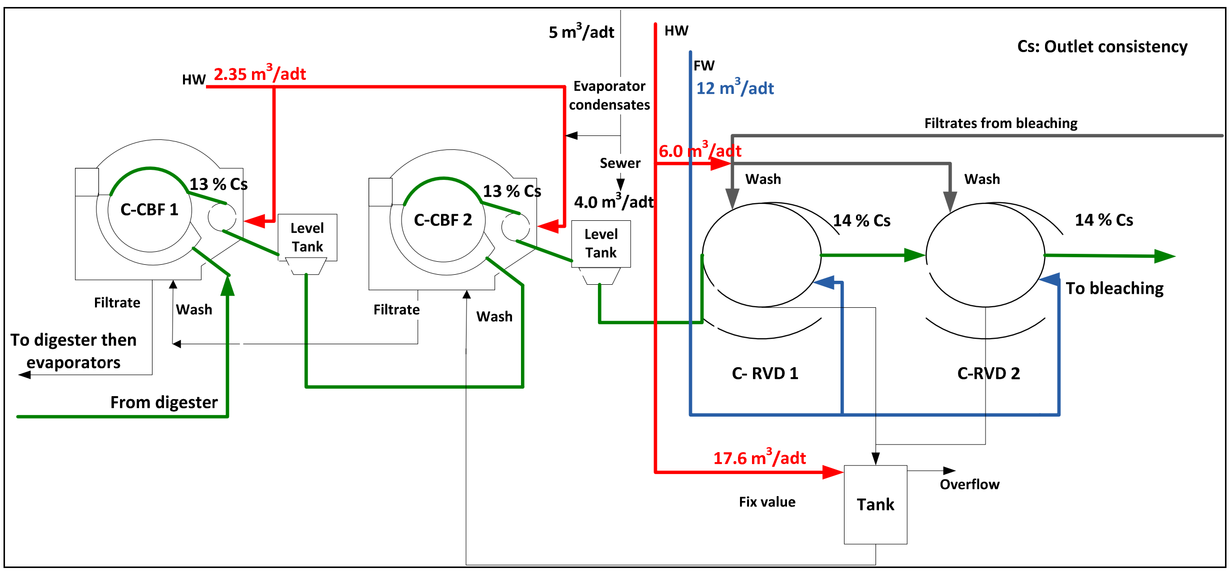

Figure 7-19: Mill C Simplified diagram for base case.

Water, steam consumption, and dissolved solids in the outlet pulp of the brown stock washer are presented in

Table 7-13: Mill C Base case, water and steam consumptions, and Ds% in pulp.

Section	Water Consumption [m^3/adt]	Steam Consumption [GJ/adt]	DS out in pulp [%]
Brown stock	38	-----	**0.04**
Bleaching	35.3	2.11	-----
Evaporator	-----	2.91	-----
To rest of the process	13.6	16.68	-----
Total	86.9	21.7	-----

Project C-1: Fresh water replacement with white water, control hot water and bleaching filtrates to DF of 2.5, temperature control of HW to sealed tank

The C-1 project consist of simple projects, like control and piping with minor modifications in the real mill. The first implementation is the replacement of fresh water (4°C) with white water (55°C) from the pulp machine, which has a high temperature. According to Turner (2001) white water can be used to replace fresh water in wire cleaning. The second suggestion is the installation of a controller in the shower of the C-RVD1 and C-RVD 2 to control the DF to the typical value of 2.5, which is currently 6.72 in the base case. The impact of such implementation will be the elimination of hot water.

The last project is the installation of a controller in the sealed tank to control the temperature. In the base case a flow of 17.6 m^3/adt is needed to have liquor that could be used to dilute the incoming pulp to the C-RVD 1 and C-RVD 2.

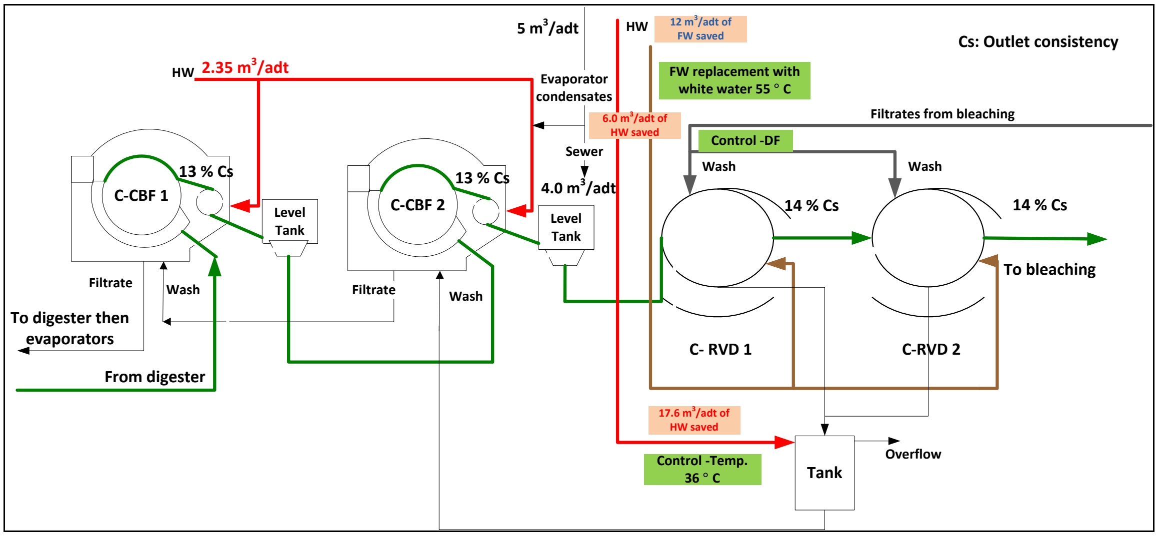

Figure 7-20 : Simplified diagram of mill C project C-1.

With the implementation of the previous projects a 37% reduction in water and 3% in steam is obtained for the mill. **Table 7-14** summarizes the consumption of steam and water after applying the projects. The pulp entering the bleaching section is much cleaner in the base case. In these projects the dissolved solids increased, but in comparison with other mills 0.15% in dissolved solids is assumed to be acceptable.

Table 7-14: Mill C Project C-1, water and steam consumptions, and Ds% in pulp.

Section	**Water Consump. [m^3/adt]**	**Steam Consump. [GJ/adt]**	**DS out in pulp %**
Brown stock	2.3	-----	**0.15**
Bleaching	37.0	2.11	-----
Evaporator	-----	2.89	-----
To rest of the process	12.86	16.37	-----
Total	52.16	21.37	-----

Project C-2: Includes project C-1, an increment in the outlet consistency in C – CBF 2, and HW replacement in bleaching, and in CBF with white water

This project comprises the increment of the outlet consistency in CBF 2, the elimination of the evaporator condensates in wire cleaning and the replacement of hot water with white water from pulp machine in C- CBF-1 and C-CBF 2.

The subproject is important, because the outlet consistency has a positive effect on the washing efficiency. The typical consistency for CBF is between 14% and 18%. In this study 18% has been chosen. The second subproject is the utilization of the evaporator condensates elsewhere to directly affect steam consumption. Also, in the base case all of the evaporator condensates were not used in wire cleaning, part of them was sent to sewer.

The project replaced a hot stream in bleaching and an effect in bleaching was observed due to the temperature of the new stream being higher at 15°C. The final subproject was the replacement of hot water used in the wire cleaning of C-CBF 1 and C-CBF2 with white water.

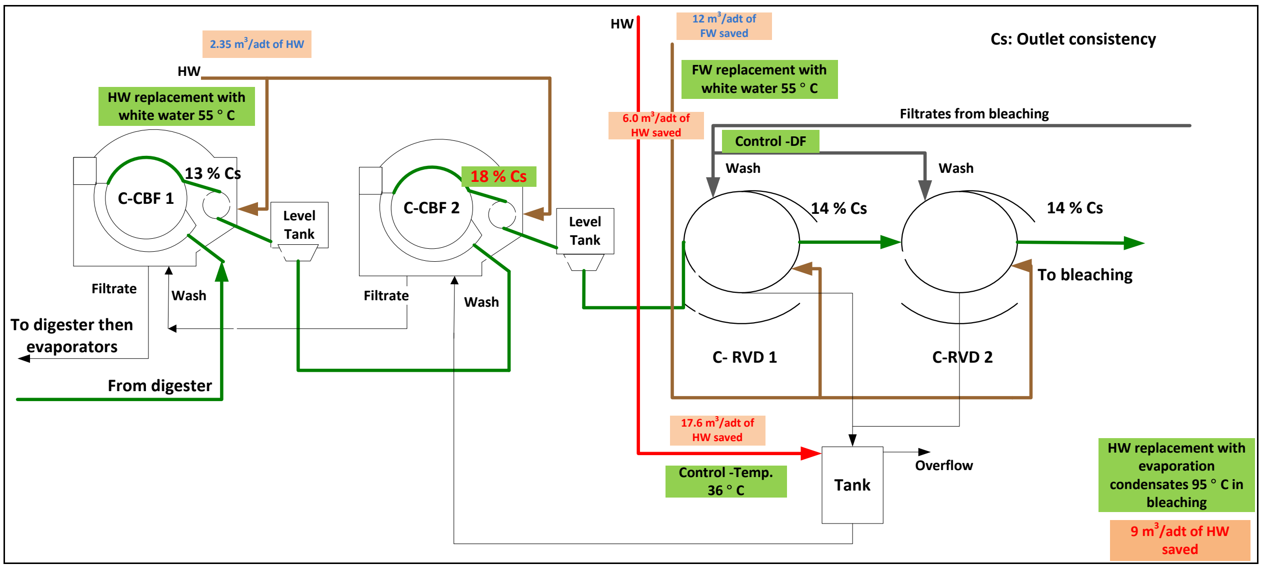

Figure 7-21: Simplified diagram of mill C project C-2.

After applying the previous sub-projects a considerable reduction of 49% in water and 7.6% in steam is obtained. The results are summarized in **Table 7-15**.

Table 7-15: Mill C Project C-2 water and steam consumptions, and Ds% in pulp.

Section	**Water Consump. [m³/adt]**	**Steam Consump. [GJ/adt]**	**DS out in pulp [%]**
Brown stock	2.3	-----	**0.05**
Bleaching	25.5	1.67	-----
Evaporator	-----	2.82	-----
To rest of the process	18.3	15.91	-----
Total	46.3	20.4	-----

The projects for mill C include subprojects that are cumulative, for example, project C-2 will include all the projects of C-1 and other subprojects. In mill C the main problems were related to the control of key variables, such as temperature, dilution factor, and key streams in the washer system.

7.2.4 Summary of all the washing projects

In the **Table 7-16** shows a comparison between the proposed projects for the three mills. As can be observed modifications in operating conditions and, in some cases, replacing or adding a new washer (high investment project) results in water and energy savings. which are vital prior to applying any process integration technique. The highest savings are achieved in mill C.

Table 7-16: Water and energy savings by improving washing performance for mills A, B and C.

Project #	Water savings (%)	Steam savings (%)	Dissolved solids (%)
A-Base case	--	--	0.16
A-1	3.3	1.8	0.35
A-2	3.4	1.8	0.04
B-Base case	--	--	0.42
B-I-1	1.0	0.3	0.42
B-I-2	1.9	0.5	0.42
B-I-3	4.3	1.6	0.42
C-Base case	--	--	0.05
C-1	37	3	0.15
C-2	49	7.6	0.05

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

An evaluation of the three partner mills was performed. For mill A can be concluded that the washers are working within the range according to the equivalent displacement ratio. For mill B line I and line II some washers were out of the typical range due to the displacement ratio specified for the type of equipment, this problem was found in the washing zone in the continuous digester and for the pressure diffuser was specified with a lower value, also the some rotary vacuum drum was much lower the typical value, currently 8% respect the typical value 12%. For mill C three of the four washers were working within the typical range of values. The equipment that was not working within the typical value was because the dilution factor was -0.88 compared to the recommended typical value of 2.5 m^3 of shower flow per adt

To increase the energy efficiency on the three Kraft mills some water and energy projects were proposed.

For mill A projects which included the elimination of non isothermal mixing points, the replacement of three rotary vacuum drums with a wash press, the heating of fresh water and chemicals with the heat removed from evaporator condensate, previously mixed with cold water in order to reach the temperature of operation of the rotary vacuum the projects reached savings in water of 3.4 % and steam in 1.8% with a diminution of dissolved solids from 0.16 % to 0.04 %. In addition of the washing projects in different departments were implemented such as recuperation of condensates, heat recovery from exhaust air from dryers, steam recuperation from flash tanks, replacement of fresh water with warm water tank overflow, heat recovery from recovery boiler to heat up combustion air mainly. The total savings in steam are 7.7 % and 11.35 % in water.

For mill B projects for line included mainly the replacement of the drum in the rotary vacuum drum and in the wash press and the addition of a rotary vacuum drum generating water saving 4.3 % and steam saving 1.6 % with a constant amount of dissolved solids of the base case of 0.42 %.

For mill C projects for line included the replacement of fresh water with white water , the control of the temperature in the tank temperature, a control of DF of 2.5 in washers C-RVD1 and C-RVD2 and increment of the outlet consistency of the C-CBF2 from 14 % to 18%. The water saving obtained were 49 % and steam saving 7.6 % with a constant amount of dissolved solids of the base case of 0.05 %.

The steam consumption for mill A is 28.2 GJ/adt. According to the benchmarking for mill A for steam consumption there are some departments with opportunity areas are digesters washing and screening, chemical recovery and for building heating. The benchmarking was done according to the average consumption in mill A with North American and European mills built in the 1990's.

The water consumption is 87.5m^3/adt. According to the benchmarking done for water consumption the departments with opportunity areas are washing and screening, pulp machine and recausticizing. The benchmarking was done comparing the water consumption for mill A against the average consumption of mill designed in the 1960's, 1980's and 2000's.

The effluent production is 67 m^3/adt, the departments generating more effluents according the benchmarking done against mills designed between 1960's and 1980's and possible future mills are pulping, washing and screening, bleaching, recausticizing, and non process water.

It was found that the Modified Norden Efficiency factor (E_{st}) is not a good parameter to evaluate washers working in mills are real or simulated conditions, due to the fact that in real mills the DF is not all the times equal to 2.5. The equivalent displacement ratio (EDR) is a reliable parameter to evaluate the efficiency in brown stock washing, when it was used in bleaching it presented illogical results like EDR higher than one, which basically means efficiencies higher than 100%. For that reason, the washing performance equations are not recommended for bleaching department.

Another conclusion is that some of the variables that affect washing cannot be evaluated in the simulation model. These variables are the effect of temperature on washing and the effect on the dissolved solids with the bleaching consumption, mainly.

8.2 Recommendations

In a simulation it is very important to set a DR that corresponds as close as possible to the equipment being evaluated and work more closely with mill personnel, especially from the washing department.

It is recommended to do more research to find a relationship between Ds% and chemical consumption, in order to evaluate the savings in a more precise manner. Also it is recommended to do a deeper research about the drawbacks of chemi-washers and typical EDR values.

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Appendix 1 – Water network

In this appendix can be observed a deviation between the intake water and effluents is 5.4 % in the Table A1-1..

Table A1-1: Water input to the system

Intake water	2238 m3/h
Effluents	2359 m3/h
Difference	-121 m3/h
% Deviation	5.41%

Table A1-2: Water input to the system

Water input to system							
ID	Tag	Description	V [m3/h]	t [°C]	E_{sp} [kJ/kg]	Q [kJ/s]	Dis_sol [ppm]
w 1	wt020, wt008	Screened water	873.6	1.4	5.8	2623.9	12.0
w2	wt022	Treated water	734.5	3.5	11.4	2446.8	12.0
Total			1608.2				
Water input by chemicals , wood chips and to non process water							
w2a		To non process	590.0	1.4	5.8	2623.9	12.0
w36		H2SO4	0.017	40.0	60.5	7.1	-
		NaClO3	0.483	60.0	153.2	40.2	-
w37		20% NaOH	2.436	15.0	52.0	48.4	-
		H2O2	0.069	17.0	70.6	1.3	-
		NaOCl	0.710	20.0	74.3	16.9	-
		SO2	0.998	110.0	462.3	1256.7	-
w38		Carbon solution	1.157	17.5	72.7	22.9	-
		20% NaOH	1.563	15.0	53.3	28.3	
w48	dp04	Chips moisture	32.1	2.0	8.3	73.2	-
Total			2238			37341.7	

Table A1-3: Screened water utilisation

Screened water utilization							
Cold water utilization							
ID	Tag	Description	V [m3/h]	t [°C]	E_{sp} [kJ/kg]	Q [kJ/s]	Dis_sol [ppm]
w3	sw02	Process water	41.5	1.5	6.2	71.9	12.0
w4	wt08	Boiler feedwater	109.8	1.4	5.8	177.1	12.0
w13	e054	Process water to evap. Surface cond.	362.6	1.5	6.2	1323.4	12.0
w5	sb08	Process water to scrubber	359.8	1.5	6.2	623.3	12.0
Total			873.6			2195.7	
w36	e059	Process water from evap. Surf. Cond.	183.6	45.0	187.7	9477.0	12.0

Table A1-4: Treated water utilization

Treated water utilization							
Cold water utilization							
ID	Tag	Description	V [m3/h]	t [°C]	E_{sp} [kJ/kg]	Q [kJ/s]	Dis_sol [ppm]
w7	h032	Fresh water to warm water tank	100.0	3.9	11.4	316.4	12.0
w8	w053, s035	Fresh water	27.1	3.9	11.4	121.8	12.0
w9	h021	Fresh water	66.6	3.9	11.4	210.7	12.0
w10	t001	Fresh Water to BL cooler	27.8	3.9	11.4	125.2	12.0
w11	h030	Fresh water to tert. Cond.	50.0	3.9	11.4	158.2	12.0
w12	cp02	Fresh water to reactor cooling coils	10.5	3.5	11.4	42.2	12.0
w14	cp03	Fresh water to York chiller	35.0	3.9	16.2	157.2	12.0
w15	rb037	Fresh water to GL cooler	0.0	3.9	11.4	0.0	12.0
w16	rl003	Fresh water to Genuit scrubber	242.2	3.9	11.4	1088.9	12.0
w28	sb22, Quench wate	Fresh water to scrubber	3.0	3.9	11.4	9.6	12.0
w30	d124, d125, d223	Fresh water to bleaching	130.1	3.9	11.4	585.1	12.0
w44	sp006	Fresh water to steam turbine cooling	181.7	3.9	16.2	816.9	12.0
w45	rl007	Fresh water to lime kiln cooling	101.0	3.9	16.2	449.6	12.0
w46	rb056, rb057	Fresh water to precoat drive and lime n	10.9	3.9	16.2	49.0	12.0
w47	e064	Fresh water to ejector train	20.0	3.9	16.2	89.9	12.0
w49	wt009	Non-process water	590.0	1.4	5.8	952.0	12.0
Total			1596.0			2815.1	

Table A1-5: Warm water generation

Warm water generation (Scrubber + Boiler feed water)							
ID	Tag	Description	V [m3/h]	t [°C]	E_{sp} [kJ/kg]	Q [kJ/s]	Dis_sol [ppm]
w4	wt08	Boiler feedwater	109.8	1.4	5.8	177.1	12.0
w6	sb02	**Scrubber water**	543.6	34.0	141.6	21253.4	12.0
Total			653.3			21430.5	

Table A1-6: Warm water utilziation

Warm water utilization							
ID	Tag	Description	V [m3/h]	t [°C]	E_{sp} [kJ/kg]	Q [kJ/s]	Dis_sol [ppm]
w17	sw01	Scrubber water to soft water plant	221.6	34.0	0.0	8663.7	12.0
w19	sb09	Make-up boiler feed water	110.6	40.0	166.6	5080.5	12.0
w20	rb036	Scrubber water to Dregs filter	0.0	34.0	141.6	0.0	12.0
w22	h033	Scrubber water to warm water tank /he	0.0	34.0	141.6	0.0	12.0
w26	s032, p042	Scrubber water	161.7	34.0	141.6	6321.5	12.0
Total			606.2			20065.7	

Table A1-7: Direct steam injection

Direct steam inject							
w42	sp031	Steam to DA	22.9	147.5	2756.1	17523.5	0.0
w41	e118	Steam into hot water	2.0	156.9	2756.9	1563.4	0.0
Total			24.9				

Table A1-8: Hot water generation

Hot water generation		(Hot water 1 = Hot water 2 + soft water)					
ID	Tag	Description	V [m3/h]	t [°C]	E_{sp} [kJ/kg]	Q [kJ/s]	Dis_sol [ppm]
w21	rl034	Scrubber water to hot water tank/recau	112.3	34.0	141.6	4417.1	12.0
w23	h043	Hot water generated	283.7	74.0	309.4	23889.8	12.0
w18	sw05	Soft water gen.	227.1	59.3	247.6	15359.3	0.4
w40	rl033	Steam to hot water tank (recaust)	9.4	156.9	2756.9	7214.6	0.0
w43	sw13	Direct steam injection	2.0	156.9	2756.9	1546.0	0.0
Total			634.5				
w32	sw11	Soft water gen.	217.8	64.9	271.3	16093.7	0.4

Table A1-9: Hot water utilization

Hot water utilization							
ID	Tag	Description	V [m3/h]	t [°C]	E_{sp} [kJ/kg]	Q [kJ/s]	Dis_sol [ppm]
w24	w055	Hot water to 3A washer	0.0	74.0	309.4	0.0	12.0
w25	p090	Soft water to thickener, slusher	126.0	64.9	271.3	9311.4	0.4
w27	f014	Soft water to pulp machine	12.0	59.3	247.6	811.5	0.4
w33	rb035	Hot water to filter precoat drive	7.3	80.9	338.5	684.9	12.0
w29	d010, d118, d216	Hot water to bleaching	343.0	74.0	309.4	28176.0	12.0
w34	rl038	Hot water to recaustiz.	113.0	80.9	338.5	10629.3	12.0
w31	d224	Soft water to bleaching	33.8	64.9	271.3	2496.1	0.4
Total			635.1			52109.3	

Table A1-10: Effluents

Effluents										
ID	Tag	Description	V [m3/h]	t [°C]	E_{sp} [kJ/kg]	Q [kJ/s]	Dis_sol_tot [ppm]	Dis_sol_i [ppm]	Dis_sol_o [ppm]	Pressure [kPa]
E 1	s046	Brown water chest overflow	383.0	42.2	175.5	18370.2	379.3	175.4	203.8	
	s023	Hydrasieve outlet	6.6	42.8	177.6	322.7	409.4	187.3	222.1	
	Sum		**389.6**			**18692.9**				
E 2	k015	Sec. knotter rejects	85.4	85.3	319.5	8715.3	14745.7	6716.3	8029.3	
	c018	CBF filtrate tank overflow	143.0	82.1	308.5	14023.4	14394.9	6550.3	7844.7	
	Sum		**228.4**			**22738.7**				
E 3	p043	Fiber mixer RCC box outlet	22.8	22.8	94.6	593.6	25.6	24.3	1.3	
	Sum		**22.8**			**593.6**				
E 4	dr15+d	Paper machine dryer output	21.1	91.1	131.7	2951.0	0.0	0.0	0.0	
	dr36	Steam effluent dryer flash tank	1.7	117.0	2701.8	1311.7	0.0	0.0	0.0	
		Moisture out with paper	1.9							
	Sum		**22.9**			**4262.8**				
E 5	sb05	Effluent from scrubber	1.4	89.0	372.7	138.1	86.2	86.2	0.0	
	sb06	Effluent from wet fan	1.1	97.3	408.0	123.5	86.5	86.5	0.0	
	Sum		**2.5**			**261.6**				
E 6	rb042	Dregs filter to landfill	0.0	49.9	61.5	0.7	949.9	949.9	90847.5	
	rl042	Weak wash storage tank effluent	4.9	76.6	296.3	444.5	411.6	411.6	9336.7	
	rb009	RB soot blow	5.7	277.4	2787.8	4383.8	0.0	0.0	0.0	6078.7
	sp019	PB soot blow	0.9	390.2	3145.5	792.3	0.0	0.0	0	6080.7
	sp016	Blow down	1.3	100.0	419.7	143.9	0.0	0.0	0.0	
	sb04	Humidity stack gas	54.3	88.7	640.7	48262.7	0.0	0.0	0.0	
	rb059	HP PB air-preheater	3.5	275.4	1211.4	3017.3	0.0	0.0	0.0	
	Sum		**70.6**			**57045.3**				
E 7	rl020	Genuit Grits out	0.2849	69.6	252.3	23.5	3547.9	3547.9	13742.6	
	rl019	Genuit effluent	0.0	-273.1	-1110.7	0.0	0.0	0.0	0.0	
	rl042	Mud tank caustic effluent	5.0	76.6	296.3	444.5	411.6	411.6	9336.7	
	Sum		**5.3**			**468.0**				
E 8	d020	D0 seal tank overflow	269.0	45.2	188.3	13809.0	146.1	48.3	97.8	
	e210	Eop seal tank overflow	148.3	54.7	227.8	9219.4	256.1	203.1	53.0	
	d110	H seal tank overflow	127.0	37.2	154.5	5351.9	10.0	213.8	23.7	
	Sum		**544.2**			**28380.2**				
E 9	e042	Evap effluent to sewer	27.4	40.0	166.6	1257.8	0.0	0.0	0	
	e062	Steam effluent (to ejector train)	0.4	184.0	2784.3	309.4	0.0	0.0	0	1032
	e065	Effluent from ejector train	20.8	17.0	70.5	399.3	1.2	1.2	0.0	
	Sum		**48.6**			**1966.5**				
E 10	ds28	Digester effluent	**0.0**	176.3	0.0	**0.0**	0.0	0.0	0.0	
E 11	h050	Warm water tank overflow	0.0	30.4	0.0	0.0	1.2	1.2	0	
	h012	Hot water accumulator overflow	11.1	72.5	303.3	914.5	0.0	0.0	0	
	Sum		**11.1**			**914.5**				
E 12	t041	BL cooler out	**28.7**	79.9	334.6	**2588.4**	1.2	1.2	0.0	
E 13	h031	Tert. Cond. Out	**50.0**	3.9	16.2	**224.8**	1.2	1.2	0.0	
E 14	sp036	Steam to non-process	29.9	156.9	2756.9	22882.3	0.0	0.0	0.0	529
	sp037	Steam to non-process	0.4	156.9	2756.9	312.4	0.0	0.0	0	529
	sp038	Steam to non-process	3.9	156.9	2756.9	3012.3	0.0	0.0	0	529
	sp039	Steam to non-process	10.8	156.9	2756.9	8270.7	0.0	0.0	0	529
	Sum		**45.0**			**34477.8**				
E 16	cp05	Cond out of SO2 superheater	0.0010	153.9	651.8	0.2	0.0	0.0	0.0	528.99
	cp07	Cond out of SO2 vaporizer	0.0023	153.8754	651.5223	0.4166	0.0	0.0	0	528
	Sum		**0.0033**			**0.5928**				
E 17	cp10	York chiller effluent	**10.0**	3.9	16.0	**44.5**	1.2	1.2	0	
E 18	sw04	Cond out of softened water HE	8.4	100.0	419.7	936.6	0.0	0.0	0	
	wt023	Steam to AV Nackawic Chem.	0.2	156.9	2756.9	137.8	0.0	0.0	0	529
	Sum		**8.6**			**1074.5**				
E 19	rl012	Genuit scrubber to sewer	**192.7**	4.1	17.1	**908.0**	2.1	2.1	0.4	
E20	rl007a	Lime kiln cooling	101.0	8.8	36.5	1013.6	1.2	1.2	0.0	
E21	wt008	Non-process water	578.2	12.0	50.4	8094.8	1.2	1.2	0.0	
Total			2358.7			200170.2				

Appendix 2 – Steam Network

Table A2-1: Steam network-steam generated for mill A

	Description	Steam generated				Mill values
Stream		m [t/h]	Temp [C]	Press [kPa]	Q [kJ/s]	
V1	HP BB	89.77	390	6081	78435	81
V2	HP RB	149.43	391	6078	130765	143
HP produced		239.20			209200	231.00
V3a	HP to MP	18.13	391	6078	15855	
D3b	Desuperheating water	6.24	81	175	589	
V3c	MP out of turbine	63.32	219	1032	50460	
V3	MP gen.	86.34	184	1032	66776	
V4	LP gen.	173.32	157	529	132729	
v24	MP to LP	24.23	184	1032	18739	1.86
Total boiler steam production		245.77			214376	
Total process steam production		245.44			209789	

Table A2-1: Steam network-steam consumed for mill A

Stream	Description	Steam consumed				Mill values
V5	Soot blow RB	5.66	277	6079	4384	
V6	Soot blow PB	0.91	390	6081	792	
V8	MP Tankfarm	28.60	184	1032	22119	
V9	MP Digesters	12.89	184	1032	9968	
V10	MP Evaps	0.40	184	1032	309	
V11	MP blow heat rec.	13.30	184	1032	10283	
V12	HP to turbine	211.06	391	6078	184584	210
V13	MP air preheater	6.93	184	1032	5358	
V14	HP air preheaters (RB, BB)	10.02	391	6078	8761	
V15	LP Digesters	18.38	157	529	14079	
V16	LP Evaps	31.80	157	529	24349	
V17	LP Bleach	15.47	157	529	10281	
V18	LP to paper machine	19.44	157	529	14885	
V19	LP to buildg. Heating	29.88	157	529	22882	30
V20	LP to soft water	10.03	157	529	7684	
V21	LP to recaustif.	9.71	157	529	7433	
V22	LP to AV Chem.	0.18	157	529	138	
V23	LP Non-process	15.14	157	529	34278	14.16
v25	LP to ClO2 Gen.	0.003	157	529	3	
v26	Flash tank vapor to DA	0.57	132	288	431	
DA1	Steam to DA	22.89	147	288	17523	
v27	LP to DA	22.32	157	529	17093	
v28	LP to knotters	0.74	157	529	567	
v29	LP to air preheater	0.23	157	529	176.83	

Table A2-1: Steam network-condensate recovery for mill A

Condensate				
Stream	m [t/h]	Q [kJ/s]	Temp [C]	Description
D3b	6.24	588.72	81	Desuperheating
c8	156.98	23842.39	129.68	Feed water to RB
c9	93.00	14124.54	129.68	Feed water to BB
cond. consumption:	256.22	38555.64		
c1	27.57	5446.97	167.53	Tank farm cond.
c2	30.59	4110.21	115.00	Evap. Cond.
c3	8.74	1194.72	117.00	Pulp machine cond.
c4	8.03	936.62	100.00	Soft water cond.
c6	13.30	1550.22	100.00	Blow heat rec. cond.
c7	13.50	2882.91	180.59	Air preheaters cond.
	0.23	41.51	152.88	Air preheaters cond.
c8	29.88	5410.24	153.95	Buildg. Heat. Cond.
c9	27.47	1600.30	50.28	Tank farm cond.
DA2	230.94	21795.58	81.15	Boiler feed water
FW	110.61	5080.498382	40	Make up water
condensate recovered	123.80	50049.79		
cond. Loss	132.42			
% lost cond	106.96			
cond recov rate %	48.32	%		

Appendix 3 – Benchmarking

Energy Benchmarking

Table A3-1: Energy consumption and production for manufacturing bleached Kraft market pulp.

	Electricity Consumption (Kwh/ODt)*	Fuel Consumption (GJ/ODt)*	Thermal Energy Consumption (GJ/ODt)*	Thermal Energy Production (GJ/ODt)*	Net Thermal Energy Production (GJ/ODt)*
25 th percentile	586.30	27.10	16.59	14.98	0.94
Median	666.60	30.07	19.57	16.40	3.48
75 th percentile	726.80	30.79	21.43	17.75	4.38
Modern	511.00	NA	10.90	NA	NA

The specific energy is determined from the sum of energies for the following areas in each mill: Kraft pulping, Kraft recausticizing, Kraft evaporators, Kraft recovery boiler and Kraft bleaching. The specific energy is the total energy divided by the bleached Kraft pulp production. The pulp production is expressed on an oven dried basis.

Table A3-2: Electricity consumption by pulp manufacturing areas.

	Electricity Consumption (Kwh/ODt)*			
	25 th percentile	Median	75 th percentile	Modern
Wood Preparation	9.5	22.2	31.6	22.0
Kraft Pulping-Continuous	150.5	179.5	221.3	161.0
Kraft Pulping –Batch	134.9	169.3	230.5	161.0
Kraft Pulping-M&D	166.0	190.9	208.7	NA
Kraft Evaporators-Indirect Contact	0.0	15.7	30.6	33.0
Kraft Evaporators-Direct Contact	10.0	24.5	44.7	NA
Kraft Recausticizing	23.2	32.1	47.9	56.0
Kraft Bleaching –Softwood	112.3	179.5	240.7	122.0
Kraft Bleaching -Hardwood	117.1	143.9	237.5	NA

*The specific energy vs the fuel consumed divided by the fibre produced or allocated to the expressed on an oven dried basis.

Table A3-3: Fuel consumption of pulp manufacturing areas

	Fuel Consumption (GJ/ODt)*			
	25 th percentile	Median	75 th percentile	Modern
Kraft Recausticizing	1.96	2.15	2.34	1.70

*The specific energy ivs the fuel consumed divided by the fibre produced or allocated to the expressed on an oven dried basis.

Table A3-4: Thermal energy consumption by pulp manufacturing areas

	Thermal Energy Consumption (GJ/ODt)*			
	25 th percentile	Median	75 th percentile	Modern
Wood Preparation	0.00	0.00	0.00	0.00
Kraft Pulping- Continuous	2.43	2.94	0.00	2.20
Kraft Pulping –Batch	4.33	4.94	3.81	3.50
Kraft Pulping-M&D	5.50	6.04	5.64	NA
Kraft Evaporators-Indirect Contact	5.03	5.91	6.76	3.20
Kraft Evaporators-Direct Contact	2.90	2.96	7.06	NA
Kraft Recausticizing	0.00	0.14	3.89	0.00
Kraft Bleaching –Softwood	2.57	3.41	0.44	1.70
Kraft Bleaching -Hardwood	1.62	2.33	4.65	NA

The specific enegy is the fuel consumed divided by the fibre produced or allocated to the expressed on an oven dried basis.

Table A3-5: Thermal energy consumption of product manufacturing areas.

	Thermal Energy Consumption (GJ/ADt)*			
	25 th percentile	Median	75 th percentile	Modern
Paper machine- Kraft papers	8.47	9.10	9.11	NA
Pulp machine- Steam Dryer	4.14	4.59	5.26	2.30
Pulp machine- Wet Lap	0.00	0.00	0.00	NA

*The specific energy is the fuel consumed divided by the fibre produced or allocated to the expressed on an air dried basis.

Table A3-6: Electricity consumption of common areas

	Electricity Consumption (kWh/ADt)*			
	25 th percentile	Median	75 th percentile	Modern
Water Treatment	13.80	29.00	54.60	32.00
Effluent Treatment	31.80	49.40	80.60	30.00
Effluent Treatment	34.30	47.60	70.80	30.00
General/Buildings	5.20	14.40	55.30	NA

Table A3-7: Fuel consumption of pulp manufacturing areas

	Fuel Consumption (GJ/ODt)*			
	25 th percentile	Median	75 th percentile	Modern
General /Buildings	0.00	0.04	0.07	NA

*The specific energy is the fuel consumed divided by the fibre produced or allocated to the expressed on an air dried basis.

Table A3-8: Thermal energy consumption of common areas

	Thermal Energy Consumption (GJ/ADt)*			
	25 th percentile	Median	75 th percentile	Modern
Water Treatment	0.00	0.00	0.00	NA
Effluent Treatment	0.00	0.00	0.00	NA
Effluent Treatment	0.00	0.00	0.17	NA
General/Buildings	0.00	0.19	0.51	NA

*The specific energy is the fuel consumed divided by the fibre produced or allocated to the expressed on an air dried basis.

Table A3-9: Fuel consumption of boiler areas

	Thermal Energy Consumption (GJ/GJ)*			
	25 th percentile	Median	75 th percentile	Modern
Power boilers	1.28	1.38	1.67	1.2
Kraft Recovery Boiler –Low odor	1.45	1.56	1.65	1.40
Kraft Recovery Boiler – Direct contact	1.79	2.02	2.13	NA

*The specific energy is the fuel consumed divided by thermal energy produced by the boiler.

Table A3-10: Thermal energy consumption of product manufacturing areas.

	Thermal Energy Consumption (GJ/GJ)*			
	25 th percentile	Median	75 th percentile	Modern
Power boilers	0.00	0.02	0.06	0.00
Kraft Recovery Boiler –Low odor	0.11	0.14	0.19	0.05
Kraft Recovery Boiler – Direct contact	0.14	0.16	0.17	NA

*The specific energy is thermal energy consumed by the thermal energy produced by the boiler.

Table A3-11: Fuel consumption of Kraft recovery boilers

	Thermal Energy Consumption (GJ/ODt)*			
	25 th percentile	Median	75 th percentile	Modern
Kraft Recovery Boiler –Low odor	26.16	28.78	29.61	NA
Kraft Recovery Boiler – Direct contact	22.34	26.39	30.79	NA

*The specific energy is the fuel consumed divided by the fibre produced or allocated to the expressed on an air dried basis.

Table A3-12: Net thermal energy production of Kraft recovery boilers

	Thermal Energy Consumption (GJ/ ODt)*			
	25 th percentile	Median	75 th percentile	Modern
Kraft Recovery Boiler –Low odor	13.45	14.63	16.72	NA
Kraft Recovery Boiler – Direct contact	9.66	10.58	11.84	NA

*The specific energy is the fuel consumed divided by the fibre produced or allocated to the expressed on an air dried basis.

Table A3-13: Steam consumption of deareators

	%			
	25 th percentile	Median	75 th percentile	Modern
Deaerator	0.00	0.04	0.07	NA

*The specific energy is the fuel consumed divided by the fibre produced or allocated to the expressed on an air dried basis.

Water consumption benchmarking

Average water consumption was calculated according to Chandra (1997). The following table presents the water consumption for mills categorized in three ways: the older mills (1960s), the newer mills (1980s), and for the mills currently being designed, which means mills designed in 1990s.

Table A3-14: Water consumption benchmarking (Subhash Chandra, 1997)

	Kraft mill effluent unit discharges (m^3/adt)		
	Older Mill	Newer mill	Current design
Woodroom			
Digesting	1.1	1.0	0.2
Washing & Screening	4.2	1.8	0.2
Bleach Plant			
- acid	25	21	5
- alkaline	30	10	5
Chemical preparation	0.5	0.8	0.2
Total fiberline	60.8	34.6	10.6
Pulp machine			
- Rejects	1.3	1.3	0.2
- General	5.2	4.9	0.2
Total pulp machine	6.5	6.2	0.4
Evaporators	0.7	0.6	0.2
Recovery	2.1	0.6	0.2
Hog / Power boiler	4.9	0.9	0.5
Recausticizing	2.6	1.3	0.3
Total recovery/power	10.3	3.4	1.2
Grand total	77.6	44.2	12.2

Effluent production benchmarking

Average effluent production consumption was calculated according to the information presented below where flows are presented under steady state operating conditions, for summer conditions, for bleached hardwood Kraft pulp. As for water production, mills were categorized in three ways: the older mills (1960s), the newer mills (1980s), and the mills currently being designed, which means mills designed in the 1990s.

Table A3-15: Effluent production benchmarking (Turner et al., 2001)

	Kraft mill effluent unit discharges (m^3/adt)		
	Older Mill	Newer mill	Current design
Woodroom	0.3	0.3	0.3
Digesting	1.1	1.0	1.0
Washing & Screening	4.2	1.8	0.5
Bleach Plant			
- acid	48.0	21.1	10.5
- alkaline	25.0	10.0	10.6
Pulp machine			
- Rejects	1.3	1.3	0.7
- General	5.2	4.9	4.9
Evaporators	0.7	0.6	0.4
Demineralization	0.1	0.1	0.1
Recovery	2.1	0.7	0.2
Hog / Power boiler	4.9	3.3	1.0
Recausticizing	2.6	1.4	1.1
Chemical preparation	0.5	0.8	0.3
Water supply	9.2	8.1	2.7
Effluent treatment	1.6	0.0	1.2
Clear water By-pass	0.0	16.6	0.0
Total	106.8	72.0	35.5

Appendix 4 – Modified Norden factor efficiency, (E_{10}) and displacement ratio, (DR) for different washers

Figure A4-1: Modified Norden efficiency factor, (E_{10}) (Poulin, 2010)

WASHER	CONS.IN %	CONS.OUT %	E_{10}
HI-HEAT (2-4 H)	10	10	6.0 – 9.0
PRESSURE DIFFUSER	10	10	5.0 – 5.5
1-STAGE DIFFUSER	10	10	3.4 – 4.0
2-STAGE DIFFUSER	10	10	6.5 – 7.5
WASH PRESS	3 – 6	28 – 35	4.0 – 5.0
PRO-FEED	3 – 4	12 – 14	3.5 – 4.5
C-B FILTER	3 – 4	12 –16	3.5 – 4.5
GF-FILTER	1 – 2	12 –16	3.5 – 4.5
1-STAGE DD-WASHER	8 – 10	12 –16	5.0 – 6.0
1.5-STAGE DD-WASHER	8 – 10	12 –16	6.5 – 8.0
2-STAGE DD-WASHER	8 – 10	12 –16	9.0 – 10.5
3-STAGE DD-WASHER	3 – 10	12 –16	11.0 – 13.0
4-STAGE DD-WASHER	3 – 10	12 –16	14.0 – 15.0

Figure A4-2: Digester Wash Zone performance, (DR),(Poulin, 2010)

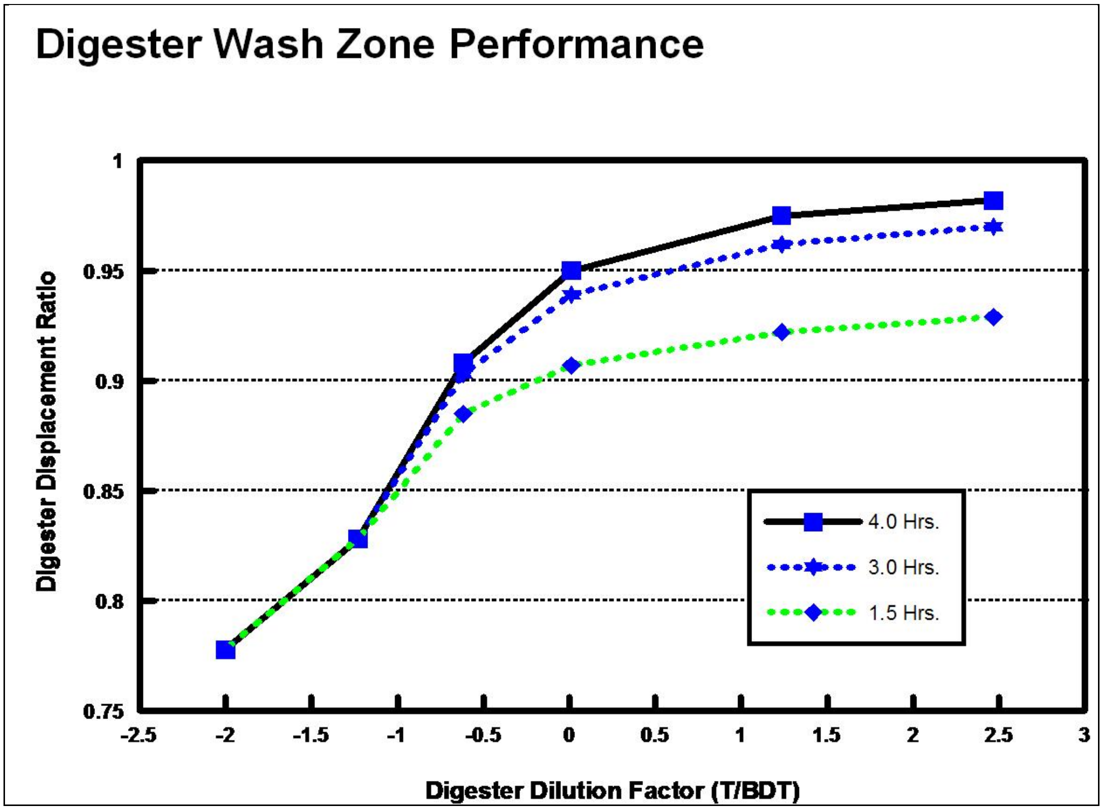

Figure A4-3: Atmospheric diffuser (DR),(Poulin, 2010)

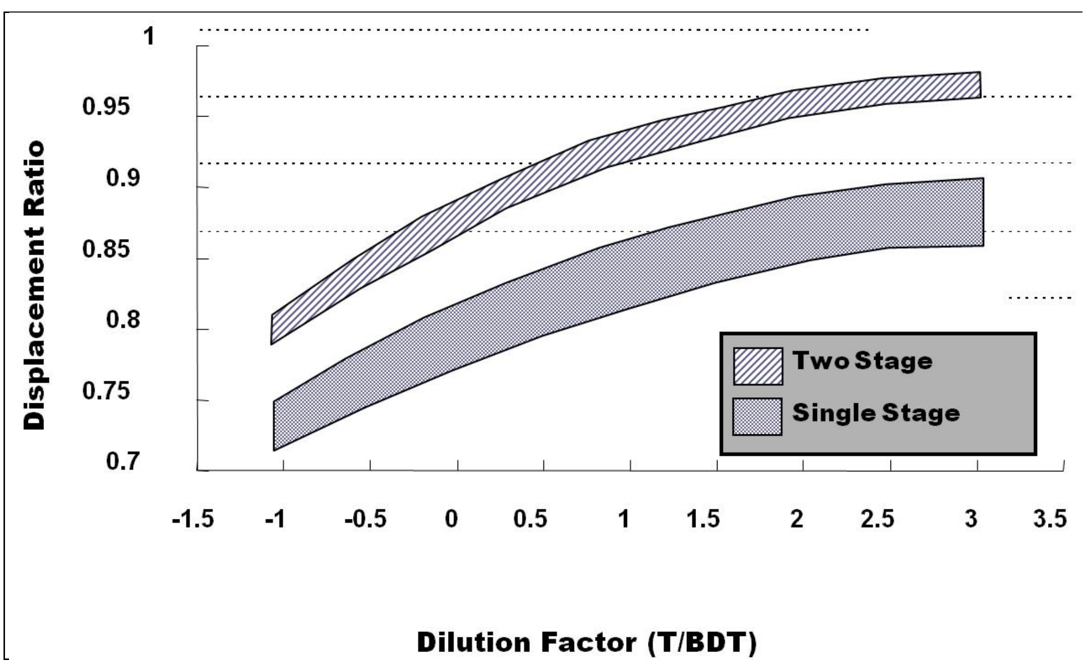

Figure A4-4: Displacement ratio, (DR) for Pressure diffuser (Poulin, 2010)

Appendix 5 – Validation table for water and steam for mill A

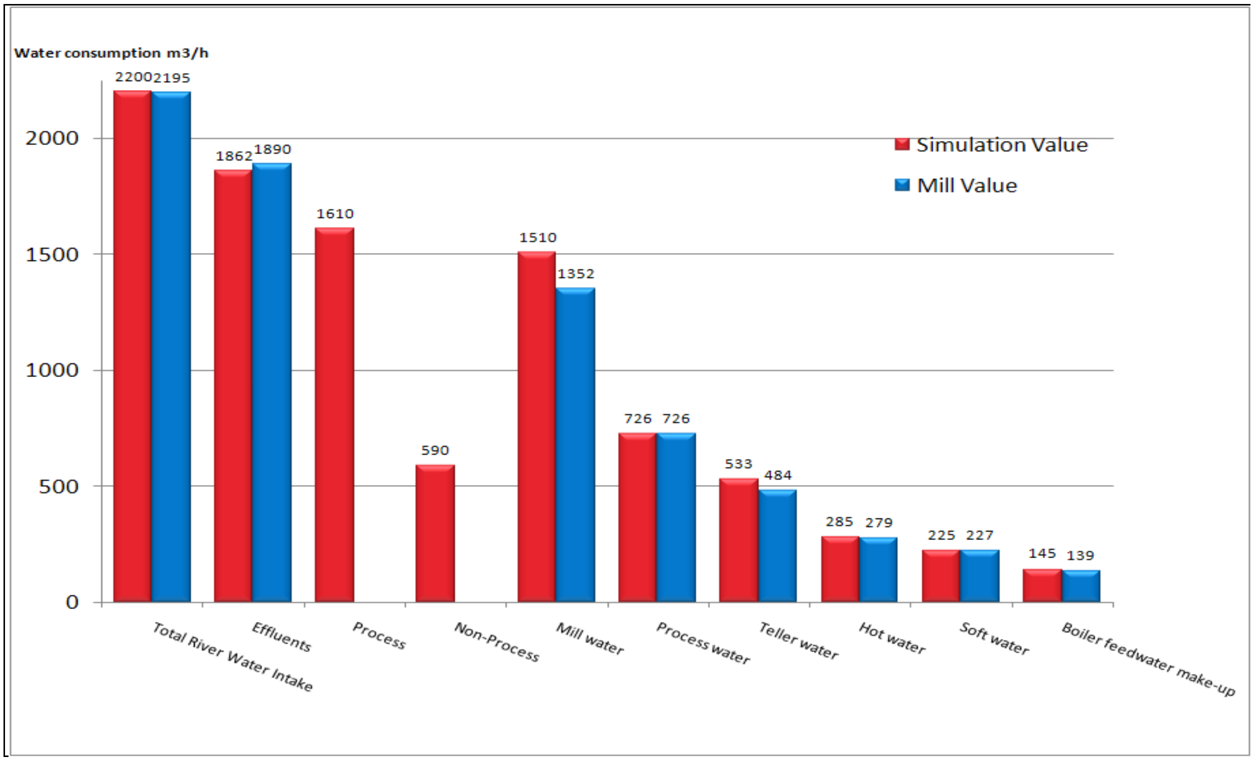

Table A5-1: Mill A water consumption comparison between simulation and mill data.

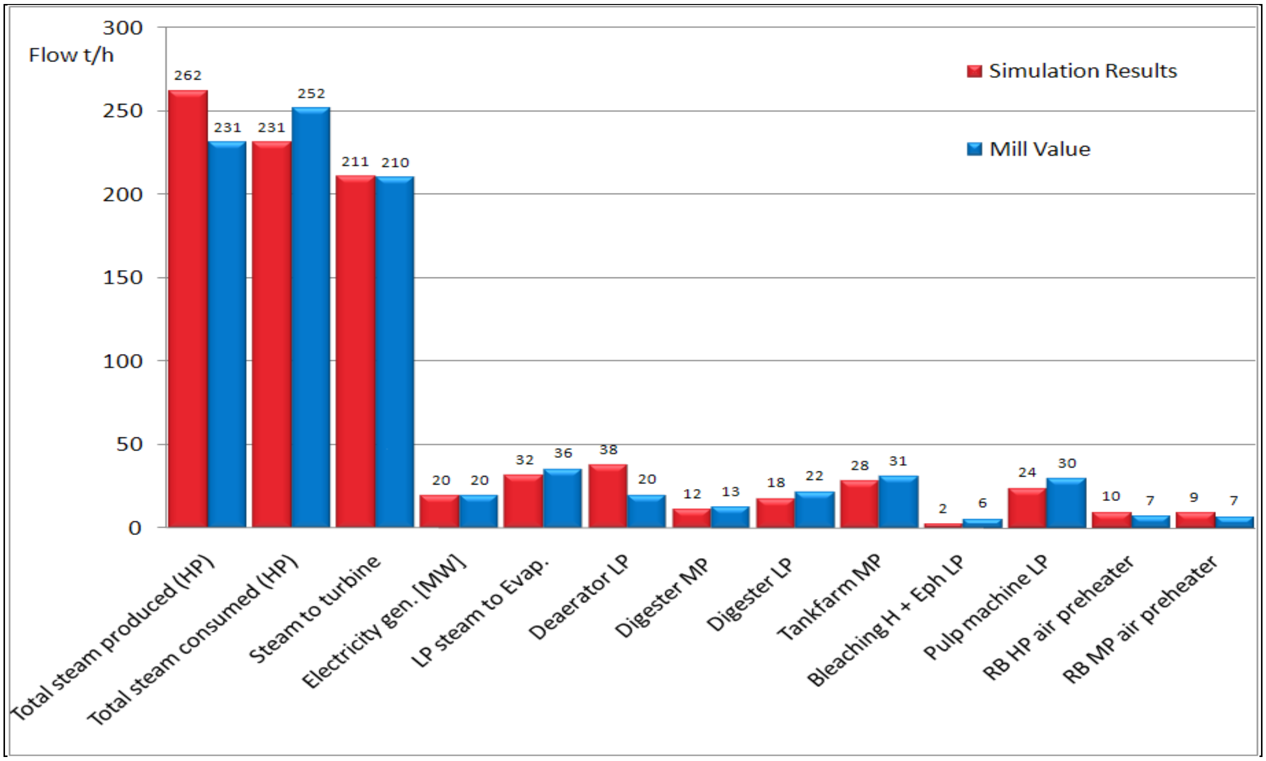

Table A5-2: Mill A steam consumption comparison between simulation and mill data.

Appendix 6 – Key performance indicator for evaporators

Evaporators

The basic requirements of black liquor evaporators are to make efficient use of steam required for evaporation, efficiently separate water from black liquor with respect to chemicals in the condensate and concentrate black liquor to solids levels acceptable for firing in the recovery boiler.

The first evaporators used were the rising film short-tube, vertical multiple effect evaporators (STV) followed by long tube vertical evaporators (LTV) concentration the dissolved solids up to 50%. Around 1980's the rising film evaporators were changed to falling film evaporators and nowadays all the new evaporators are based in that technology.

The advantages of the falling film evaporators over the rising film evaporators are principally.

- High steam economy because of better transfer rate.
- Low temperature differential (dT) permits more number of stages/effects.
- Low operating cost due to lower consumption of steam and power.
- Higher availability due to less fouling.
- Ease of incorporating condensate segregation system.
- Low alkali carry over to condensate.

The percentage of solids that can be achievable in the falling film evaporator is no more that 70% - 75%. Nowadays modern pulp and paper mills have between 6 and 7 effects evaporation plant with condensate and stripping equipment. The new trend in mills is to burn black liquor with a concentration of 80% solids. The problem if the percentage of dissolved solids is above 70 % is the viscosity. To solve the viscosity problems and to enable the evaporation plant to produce 80% solid liquor with concentration highers than 80%, a process called Liquor Heat Treatment (LHT).

The key performance indicator for evaporator is the economy which is defined by the mass of water evaporated divided by the mass of steam consumed. For a single effect the maxium economy that can be reached is one, for a multiple effect the economy for a every single effect will be less than one.

The vapor recompression is a technique used to increase the economy of the evaporators, which consist in the use of a compressor to increase the quality of the steam used between effect. Also heat recovery can be done to heat the black liquor between stage reducing the steam consumed or increasing the concentration of dissolved solids between stages.