Pinch analysis of the Norske Skog Skogn TMP mill

Potential for steam savings in TM2B and PM1

Master's Thesis within the Sustainable Energy Systems and Innovative and Sustainable Chemical Engineering programmes

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Cover:
Picture of Norske Skog Skogn mill, photographer: Moa Festin

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ABSTRACT

Energy conservation measures can bring important environmental and economical benefits to the most energy-intensive industry sectors such as the pulp and paper industry. The measures include among others investing in more energy efficient process equipment and improving process integration. A tool that has successfully been used in pulp and paper mills to improve process integration and achieve steam savings is pinch analysis

In this master's thesis, a pinch analysis of one part of a thermo-mechanical pulp (TMP) mill, Norske Skog Skogn, is presented. The study aimed at improving the process integration and to decrease the steam demand of the mill. Additionally, the effect of decreasing the electricity consumption was studied for two different scenarios: when certain amount of the electricity-intensive mechanical pulp is replaced with recycled paper and fillers and/or when implementing more energy efficient refining.

The results showed that investing in measures that decrease the electricity consumption of the mill can lead to an insufficient production of internal steam and consequently to an increased demand of external steam to cover the deficit. Another way to cover the deficit of steam is to decrease the steam demand of the process by improving process integration. Pinch analysis was used to identify the major sources of inefficient heat exchange i.e. pinch violations in the system and to propose three retrofits that improve the heat exchanger network. Apart from these three retrofits focusing on the heat exchanger network, two additional retrofits, not connected to the heat exchanger network, were also investigated. These were preheating of certain streams and the integration of a heat pump.

The major source of pinch violations is the paper machine heat recovery system, the cooling system and the district heating system. In the proposed retrofits the total clean steam consumption is decreased by improved process integration. In the first retrofit 1.1 MW of clean steam (4 % of the total clean steam consumption) are recovered by solving pinch violations mainly associated with the district heating system. In the second and third retrofits 2.2-2.8 MW (8 %-11 %) respectively of savings are achieved by modifying the paper machine heat recovery system and the district heating system. By investing in a reboiler with higher capacity and preheating certain streams it is possible to save 4.6 MW (18 %) clean steam. Finally, by integrating a heat pump it is possible to reduce the clean steam consumption by 3.5 MW (13 %). The combination of the previous retrofits makes it possible to reduce the total clean steam consumption by 8.9MW (34 %).

Key words: Pinch analysis, thermo mechanical pulp mill, TMP mill, steam saving, process-integration.

Contents

Preface

This report presents the results of a Master's thesis carried out in cooperation between the Division of Heat and Power Technology at Chalmers University of Technology, Paper and Fibre Research Institute and Norske Skog Skogn. The study was a part of the research project ENPAP, a cooperation between PFI (Paper and Fibre Research Institute), Norske Skog, Voith, News International and others, with the aim of reducing the energy usage at Skogn mill.

The study is a pinch analysis of the Norske Skog mill Skogn located near Trondheim in Norway. The objective of the thesis was to identify potentials of steam savings through improved process integration.

We would like to express our gratitude to our examiner Thore Berntsson, our supervisor Johanna Jönsson and our mentor Erik Axelsson, for their guidance and support. We would also like to thank Kai Toven, Lars Johansson and Øyvind Eriksen at PFI in Trondheim for their help during the time in Norway.

Finally, we want to thank Arnt Ove Grønli, Tormod Røstad and Terje Rian at Norske Skog Skogn mill, for all the help we got when we arrived and during our time at Skogn. Their help and the help from other employees at Skogn were crucial for our work with this thesis.

Göteborg June 2009

Moa Festin and Valeria Mora

Notations

°C	Centigrade degree
AC	Alternating current
AD	Air-dried (90 % dryness)
BD	Bone-dried (100% dryness)
BTU	British thermal unit
CC	Composite curves
CF	Cloudy filtrate
CO_2	Carbon dioxide
Cp	Heat capacity
DC	Direct current
DIP	Deinked pulp
F	Flowrate
g	Gram
GCC	Grand composite curve
GWh	Gigawatt-hour
H	Heater
HX	Heat exchanger
h	Hour
J	Joule
kg	Kilogram
kJ	Kilojoule
kPa	Kilopascal
kW	Kilowatt
kW	Kilowatt
l	Litre
lb	Pound
LC	Low consistency
m	Meter
m	Flowrate
m^2	Square meter
m^3	Cubic meter
MER	Maximum energy recovery
MJ	Megajoule
mm	Millimetre
MW	Megawatt
MWh	Megawatt-hour
PFI	Paper and Fibre Research Institute
pH	Hydrogen potential
PI	Process integration
PM1	Paper machine 1
PM2	Paper machine 2
PM3	Paper machine 3
Qvvx	Total heat transferred in a heat exchanger
s	Second

t	Ton
TM1	Pulp line 1
TM2A	Pulp line 2A
TM2B	Pulp line 2B
TMP	Thermo-mechanical pulp
TWh	Terawatt-hour
W	Work
yr	Year
Δh	Enthalpy difference
ΔT	Temperature difference
ΔT_{min}	Minimum temperature difference

1 Introduction

To decrease energy use in order to achieve a sustainable society is one of the biggest challenges which the humanity is confronting. For the industrial sector, one of the key actors towards achieving this goal, energy conservation measures can in addition be very profitable.

The pulp and paper industry is one of the most energy-intensive industrial branches. This branch is the sixth-largest industrial energy user in Europe, using approximately 370 TWh of thermal energy and 120 TWh of electricity during 2006 [1]. Additionally, the pulp and paper industry is the largest industrial user of renewable fuel in Europe. Seen to the industrial energy use in Europe, the pulp and paper industry is especially dominant within the Scandinavian countries' industry sectors. In Norway, the pulp and paper industry used about 11 TWh of energy in 2007 compared to 80 TWh of the entire Norwegian manufacturing sector [2].

Paper pulp can be produced in three different ways: mechanical, chemical and semi-chemical process. In the mechanical pulping process the wood is grinded down into fibers through mechanical work. In chemical pulping, only some of the wood becomes fibres and the rest is dissolved. The semi-chemical pulping is a combination of mechanical and chemical pulping as the wood chips are chemically treated before the mechanical pulping [3]. The mechanical pulping process demands the highest amount of electricity per ton pulp produced compared to the chemical and semi-chemical pulping process [4].

The main methods of producing mechanical pulp is; stone groundwood pulping, refiner pulping, thermomechanical pulping and recycled paper pulping. When producing thermomechanical pulp (TMP) wood chips are first steamed in order to become softer before the refining. It is the refining which consumes most electricity, the majority of the electrical energy transforms into heat in the refiner and leaves as steam. The steam is recovered in a steam recovery system, where it is transformed into clean steam that is used to satisfy partly or the total steam demand of the pulp and paper process, for instance: in the paper machine drying section [3].

As recycled paper pulping uses paper as raw material instead of wood the production of recycled paper pulp demands less electricity. A way to decrease the total electricity use in a TMP and paper mill is to produce less electricity intensive TMP and replace this reduction with recycled paper (deinked paper, DIP) and/or filler. Another way to decrease the use of electricity is to use more efficient refining techniques [3]. However, when less electricity is used in the refiners, or when less TMP is produced, less steam is also produced. This means that if no investments in reducing the steam demand of the plant are done simultaneously, additional, fuel based, steam production will be needed.

Pinch analysis is a method which has been used in many energy-intensive industries, as pulp and paper industries, to achieve steam savings [3]. Earlier studies with pinch analysis have been carried out at mills producing chemical pulp in North America and in Europe, as chemical pulping mills are most common in these parts of the world. In Canada, pinch studies have been carried out on TMP mills [5] but in Scandinavia, a large producer of both chemical and mechanical pulp, only few pinch analysis have been made on TMP mills. These studies have been mostly done on model mills rather than on real TMP mills.

Axelsson [6] investigated the opportunities of increasing the steam surplus of a model TMP mill by improved process integration through pinch analysis. The model mill had the best commercially available and reliable equipment used in Scandinavian pulp and paper mills. The mill was energy self sufficient and even had a surplus of steam. After process integration the mill had a 41% higher steam surplus and the cooling demand decreased by 49%. This proved that even though the TMP plant was designed with the best available technology, the potential for improvements via pinch analysis was significant.

This thesis contributes to further information about the potential of steam savings on a real TMP mill in Scandinavia.

1.1 Objective

This master thesis aims at analyzing the energy situation of a real TMP mill within the Norske Skog group by means of pinch analysis. The objective is to identify retrofits to the studied system which reduce the process steam consumption by improved process integration. Further, the goal is to analyze how a future introduction of recycled paper and fillers with or without investments in more energy efficient refining would affect the energy situation at the mill. To reach these objectives the following questions are addressed:

- What is the current steam demand and steam production within the system?
- How is the steam demand decreased by improved process integration?
    - How much can the steam demand be reduced by improved internal heat exchange (solving pinch violations)?
    - What are the effects of increased preheating of suitable streams?
    - What is the effect of integrating a heat pump in the system?
- How is the energy situation at the mill affected by a future introduction of recycled paper and filler? And what would the effect of improved process integration be in this future scenario?
- How is the energy situation at the mill affected by investments in more energy efficient refining? And what would the effect of improved process integration be in this future scenario?

1.2 Scope

The boundary of the studied system is around one paper machine and the corresponding pulp production, at the Skogn mill owned by Norske Skog. Auxiliary systems as district heating, steam utility and cold utility are included as much as they are used by the paper machine and the pulp plant.

The pinch analysis was performed during the spring 2009 after a rebuild of the studied fiberline but before any introduction of recycled paper and filler.

The thesis focuses on the steam saving potential of the system through improved process integration. Consequently, economic and environmental analysis is outside the scope of this study.

1.3 Methods

The work of this thesis consisted mainly of a literature study, data gathering and analyzing steam saving potentials through process integration using pinch analysis.

The data was collected during two stays at the Skogn mill. During these stays much time was spend to get familiar with the process of pulp and paper production. In the data gathering a computer model of the mill, flow sheets as well as printouts from the controller screens and information from operators were used. The mill model, called FlowMac, was constructed by Øivind Opdal at Norske Skog in the simulating program Extend version 6 Runtime. As the process for pulp and the paper production is complex, the model was a good tool to identify streams of interest for the pinch analysis. Parts that were missing in the model were modelled in the process simulation program Aspen HYSYS, see Appendix 5. For future introduction of recycled paper and filler and/or investments in new refiners, for which no steam data was available, data for the existing mill was used but adjusted to changes in pulp production and electricity consumption respectively.

The main method used in the thesis is pinch analysis, which is further described in Chapter 2.

2 Pinch Analysis

Pinch analysis is a method for finding process integration opportunities. Process integration aims at minimizing the need for hot and cold utilities through maximizing internal heat recovery. The approach can be used for grass root design or for evaluation and retrofit of existing heat exchanger networks [7]. In this thesis an existing network is evaluated and possible retrofits are suggested.

In a pinch analysis, the maximum theoretical internal heat recovery is studied. A heat exchanger network which meets this maximum target of internal heat exchange and thus minimizes the consumption of external heat and cold utilities is called a maximum energy recovery (MER) network. With pinch analysis, it is possible to systematically identify the reasons to why an existing system consumes more hot and cold utilities than the ideal MER network. In a retrofit study, the energy recovery target depends on thermodynamic constraints and economic limitations. The energy recovery target is rarely the same as the theoretical internal recovery as the investment cost increases with increasing internal heat recovery. The ultimate design is therefore dependant on economic constraints. This is of importance in the case of retrofitting studies in which the target may consist on few highly energy and cost efficient changes, rather than designing a MER network.

Any process can be viewed as an aggregate of streams between different process units. The temperature of these streams may be fixed by certain process restrictions, storage specifications or environment conditions. The temperature specifications can be met either by heat exchanging with hot and cold utilities or by heat exchange with other process streams.

According to pinch analysis, information about streams such as temperature and heating or cooling demand can be used to calculate the maximum possible internal heat recovery. This is done by examining all the streams that exist in small intervals of temperature and calculating if the interval has a net heating demand or a net cooling demand. If the streams in an interval have an excess of heat, it is assumed that they can transfer heat to an interval at a lower temperature. Normally, the system has a net deficit of heat above a certain temperature and an excess of heat below that temperature. This temperature is called the pinch temperature.

Based on pinch analysis it is possible to find the pinch temperature, the minimum heating and cooling demand and the theoretically possible internal heat recovery. Any deviation from the maximum recovery may be explained according to violations against one or more of the pinch golden rules [7], namely:

- Heaters should not be placed on streams below the pinch as this is a section with excess of energy (any heat added will increase the cooling demand)
- Coolers should not be placed on streams above the pinch as this is a section with heat deficit (any heat removed will increase the heating demand)
- Heat transfer from streams above to streams below the pinch should be avoided (removing heat from a stream with heat deficit to add it to a stream with heat surplus increases both the heating and cooling demand)

The steps for conducting a pinch analysis can be summarized as:

1. Definition of relevant stream system
2. Gathering of stream data such as heating or cooling demand and temperatures
3. Definition of a minimum temperature difference allowed for heat exchanging between streams
4. Construction of composite curves (CC) and grand composite curve (GCC)
5. Calculation of maximum internal heat recovery and minimum heating and cooling demand
6. Identification of pinch violations
7. Analysis of existing heat exchanger network and possibilities for retrofit.

2.1 The composite curves

Composite curves are temperature/enthalpy diagrams of the stream network. They consist of a hot composite curve and a cold composite curve. The hot composite curve is constructed by calculating total heat content of all the hot[1] streams at the various temperature intervals. The cold composite curve is constructed by calculating total heat demand of all the cold streams[2] at the different temperature intervals. The cold composite curve is placed so that the vertical distance between the hot and cold composites curves never is smaller than the chosen minimum temperature difference, ΔT_{min}, in a heat exchanger at any point of the curves.

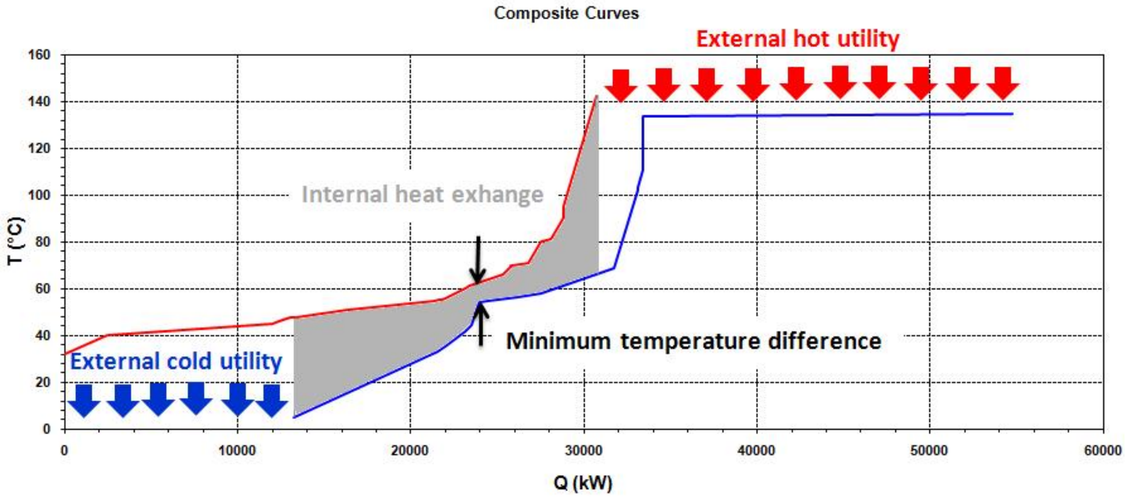

Figure 1 An example of hot and cold composite curves

Figure 1 is an example of composite curves. The overlap between the two curves represents the possibilities for internal heat exchange, represented by the shaded area. The sections of the curves which do not overlap represent the need for external heating and cooling. The external heat demand is represented by the red arrows in the figure and the external cooling demand is represented by the blue arrows in the figure.

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[1] In a pinch analysis a hot stream is defined as a stream that needs cooling (regardless of the temperature of the stream).

[2] In a pinch analysis a cold stream is defined as a stream that needs heating (regardless of the temperature of the stream).

The temperature at which the curves approach each other with the smallest temperature difference is the pinch temperature.

2.2 The grand composite curve

The grand composite curve is also a temperature/enthalpy diagram of the stream network and shows the variation of heat supply and demand within the process. The GCC is constructed by adding all the hot and cold streams of the process for different interval temperatures. The difference between the composite curves and the grand composite curves is that in the former a cold curve and a hot curve are represented whereas in the latter an overall curve is constructed. The grand composite curve can be used to identify the minimum hot and cold utility demand and the pinch temperature. Additionally, the grand composite curve can be used for studying different possibilities for integration of other units such as heat pumps.

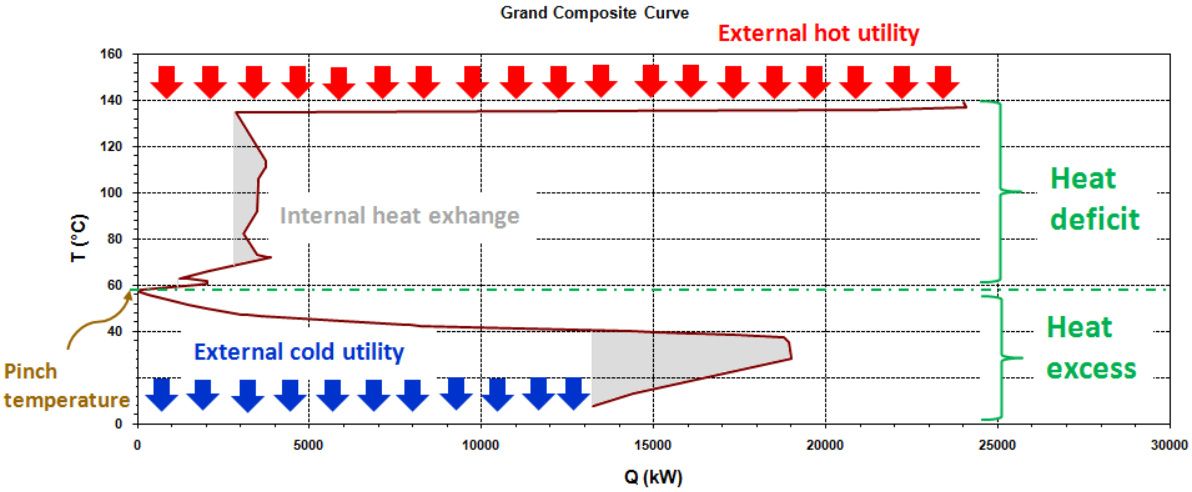

Figure 2 An example of a grand composite curve

Figure 2 is an example of a grand composite curve. The temperature at which the net heat equals zero (when curve touches the y-axis) is the pinch temperature. Above the pinch, the system has a deficit of heat; below the pinch the system has an excess of heat. The external heating demand is represented by the red arrows in the figure and the external cooling demand is represented by the blue arrows in the figure.

2.3 Retrofit pinch analysis

As previously mentioned, the goal of a pinch analysis is to maximize internal heat recovery in a grass root design or in a retrofit design. A grass root design is the proposal of a process that is not built yet whereas a retrofit design is the proposal to modify an existing process. The way the pinch analysis is done varies between these two design options.

A retrofit pinch analysis consists of four main steps: 1) data extraction, 2) retrofit targeting, 3) retrofit design and 4) network optimization. The first step consists of drawing the system boundaries and to gather the data needed for the analysis, i.e. information about the streams temperatures and their heating or cooling demands. The information is collected from different sources like on-site measurements or process flowsheets. If information is not available, auxiliary tools may be used, for example simulation models. This first step is common for both grass root design and retrofit design.

The second step of a retrofit pinch analysis is to set a retrofit target. The target is a compromise between the benefit of the utility savings and the retrofit investment cost. In a retrofit design, utility savings may be achieved by adding new heat exchangers, changing the size of existing heat exchangers or changing the position of existing heat exchangers.

The third step is to propose a retrofit design where it is possible to achieve utility savings by modifying the original heat exchanger network to some extent. Finding the best network design is an iterative process and it is dependent on the cost of the retrofits. In this thesis, several retrofit alternatives are presented but the results need to be complemented with an economic analysis.

The fourth step consists of optimizing the suggested design. This may include modifying the temperature of certain streams or integrating external energy equipment for example, a heat pump.

2.4 Economical aspects of pinch analysis

Several factors influence the cost of a retrofit design, for example the area needed for heat transfer and the distance between streams. The area in a heat exchanger depends on the temperatures of the streams and types of the fluids used. Some fluids have better heat transfer properties than others. Additionally, if the temperature difference between the hot and cold stream is small, a larger area will be needed. In a pinch analysis this is taken into account by setting the minimum temperature difference in a heat exchanger. If the heat transfer properties of the fluids differ, it is possible to set individual minimum temperature differences.

For a chosen minimum temperature difference, the cost of a retrofit design depends also on the magnitude of pinch violations eliminated. If all pinch violations are eliminated the internal recovery will be maximized, but more units need to be bought or modified. Therefore the retrofit cost will normally increase with increasing heat recovery. Typically, the retrofit design does not aim for maximizing internal heat recovery but for making few energy- and cost-efficient changes to the studied system.

How the retrofit shall be carried out i.e. the reduction in utility consumption in relation to the capital cost can be handled in several ways. The Matrix method [8] is a tool for economic evaluation that was developed by Chalmers Industriteknik AB. In the Matrix method, the area, piping, pressure drop and maintenance costs can be taken into account in a systematical and rigorous way to determine which the best retrofit solution is. In this thesis, time limitations hindered the use of the Matrix method.

2.5 ProPi

To facilitate pinch analysis ProPi, an application in Excel, has been developed by Chalmers Industriteknik AB. Using ProPi the composite curves and grand composite curve are constructed in an easy way. Input data to the program is the temperature levels and energy load of the streams. Additionally, it is possible to construct heat exchanger networks and identify and quantify pinch violations in ProPi. In this thesis, ProPi was used extensively.

3 The studied system – Norske Skog Skogn

In this thesis a Norwegian newsprint pulp and paper mill, Skogn mill, has been analysed. The Skogn mill, located near Trondheim, is owned by Norske Skog and has an annual newsprint paper production capacity of about 600 000 tonnes which makes it the largest pulp and paper mill in Norway. Norske Skog Skogn was founded in 1962 and the first newspaper machine started its production in 1966 [9].

The Skogn mill consists of a pulp and paper production plant and a recycle fibre plant. The mill has three paper machines; PM1, PM2 and PM3 and three pulp production lines; TM1, TM2A and TM2B. There is also one biomass preparation plant where the bark is removed from the timber and the wood chips are produced.

Hot utility is supplied by three boilers. Two of the boilers are fuelled by chips, bark, bio sludge or oil and one is an electric boiler. In the pulp production dirty steam is generated by the refiners. This dirty steam is recovered as clean steam in a reboiler. The degree of recovery is a measure of how much of the electricity put into the refiners that is recovered as clean steam in the reboiler.

At the mill there is a biological water treatment plant. The cleaned process water is let out in the Trondheim fjord. The freshwater is taken from a freshwater lake. A mass balance from 2006 is shown in Figure 3 to illustrate the whole plant.

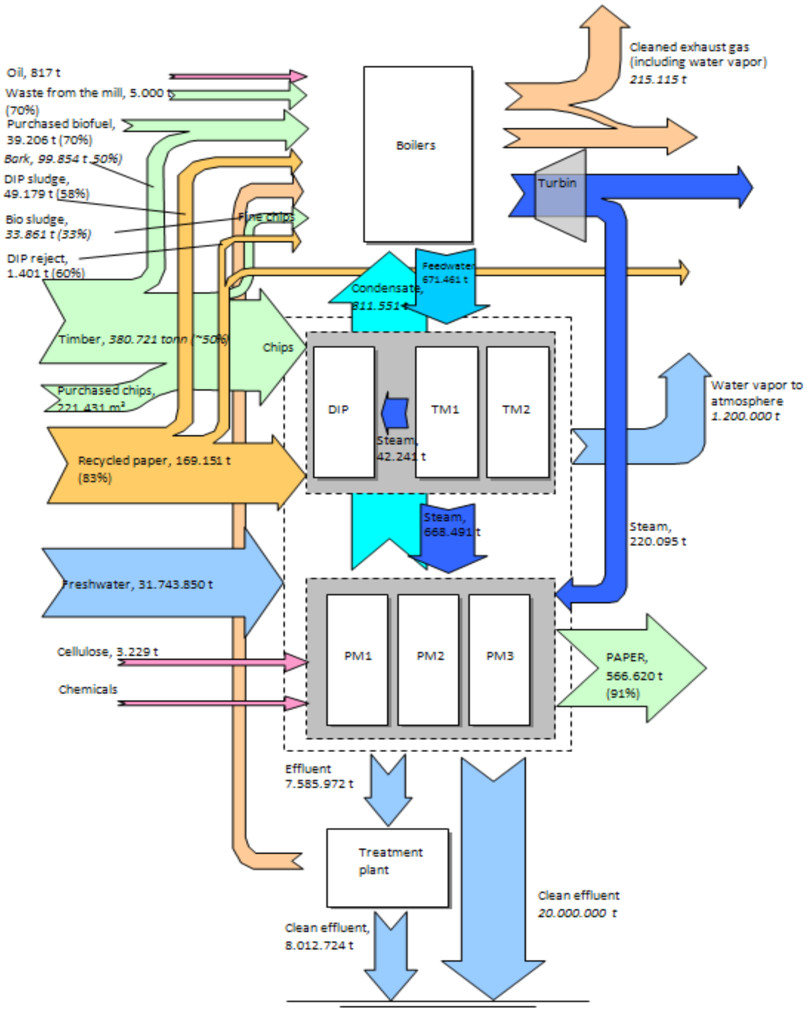

Figure 3 Mass balance from 2006 of Skogn mill [10]

3.1 System boundaries

The system boundaries of this thesis concerns the paper machine PM1 and the pulp that is needed for the paper production in PM1.The system boundaries are shown in Figure 4.

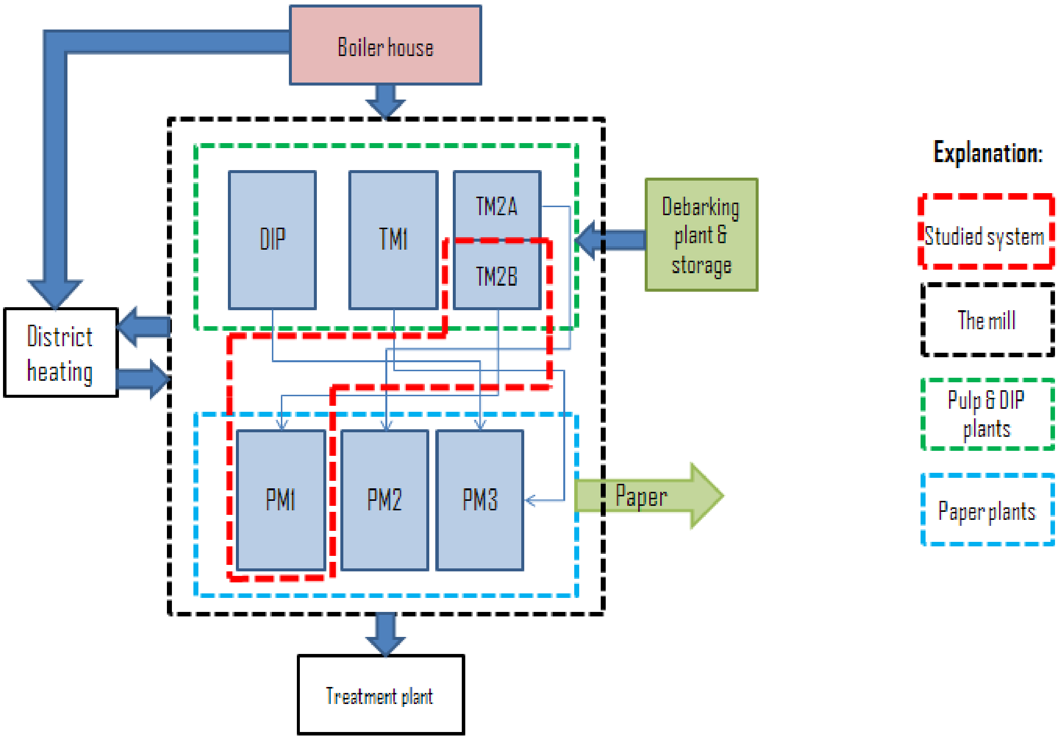

Figure 4 System boundaries of this thesis

The production of paper in PM1 is 163 000 ADt/year and the thermo mechanical pulp production in TM2B is 177 000 ADt/year, for more detailed information about the paper and pulp production see Appendix 1.

In the first part of the thesis only thermo mechanical pulp (TMP) is used on PM1. However, in a future scenario both TMP and deinked pulp (DIP) is used on PM1. The TMP for PM1 is produced in the pulp plant TM2B and the DIP is produced in the DIP plant. Currently the DIP plant only produces DIP to the paper machine PM3. In the future scenario with recycle fibers and filler, 88 percent of the DIP from the DIP plant goes to PM3 and the remaining 12 percent will go to PM1. The Skogn mill consists of several production lines with streams which are not separate for each line. In order to be able to analyze the studied system one has to exclude different parts and streams of the mill. Streams exiting the system and entering other production lines of the mill were constrained to have the same temperature in order to satisfy the surrounding system. The system was a net producer of district heating, the net was used outside the system boundaries and was therefore not included in the pinch analysis, see Appendix 6. However, the effluent streams exiting the system could be change in temperature as the treatment plant was not dependent of the streams as the other production lines were. In this way the effluent treatment plant was indirectly included in the pinch analysis.

3.2 Energy use

Pulp and paper plants are energy intensive industries and the Skogn mill is not an exception. The mill stands for about 1% of Norway's total electric energy use [11].

The total steam consumption of the mill including the turbine is 750 GWh. Out of this 199 GWh is used within the system studied in this thesis (described in Section 3.1). The total steam production from the boiler house equals to 50 % of the total steam use or 380 GWh. As mentioned above the plant has three boilers. One electric boiler and two boilers fuelled by chips, bark, bio sludge or oil. The steam produced from the different fuels is; 47% bark and sludge, 2% oil and 1 % electricity. The remaining 50 % (378 GWh) is produced in the pulp plants. The steam production at the mill is shown in Table 1 [12]. The clean steam production in the pulp line of the studied system, TM2B, is 128 GWh.

Table 1 Steam production at the mill 2008 [12]

Steam production at the mill

Sources	Steam/yr [MWh]
Steam production from the boiler house (50 %)	380 765
** Bark, sludge (47 %)*	*359 991*
** Oil (2 %)*	*12 599*
** Electricity (1 %)*	*8 175*
Steam production from the processes (50 %)	377 748
Total steam production	**758 513**

The heating and cooling demand of the system studied and the steam production and consumption are presented in Table 2-4. The calculations for each steam consumer are presented in Appendix 2. The heating and cooling demand is also presented in Appendix 3.

Table 2 Total heating demand of the studied system

Total heating demand

Hot utility	**Load [MW]**
Clean steam	26,1
Dirty steam	2,6
Total heating demand	**28.7**

Table 3 Total cooling demand of the studied system

Total cooling demand

Cold utility	**Load [MW]**
Refiner cooling	0.5
Motor cooling	0.9
Effluent cooling	8.5
Other cooling	8.0
Total cooling demand	**17.9**

Table 4 Steam production and consumption of the studied system

Steam production and consumption	
Steam users	**Load [MW]**
Press section (steam box)	1.9
Dryer	15.9
Air to dryer	1.6
Calender	0.9
Hot water	1.5
Steaming*	0.6
Preheating*	2.0
Hot dilution water	4.3
Total demand	**28.7**
Production - clean steam	16.8
Production - dirty steam	6.8
Deficit of clean steam	**9.3**
Surplus of dirty steam	**4.3**

**utilizes only dirty steam*

The total electricity consumption in 2008 was 1255GWh[3]. The largest electricity consumers are the refiners. In a recent rebuild of the TM2B plant two low consistency (LC) refiners have been installed. The LC refiners consume less energy but do not produce any steam. By installing the LC-refiners the electricity demand was expected to be reduced by 300 kWh/t[4] processed pulp, therefore the total electricity consumption per ton air dry pulp[5] for the refiners in TM2B are expected to be 1 860 kWh which equals 310 GWh/year in total. Electricity is produced in the turbine in the boiler house. The total electricity production in 2008 was 34 GWh [12], equal to 2% of the total electricity consumption.

The mill has an internal district heating system. The district heating system is used only at the mill and there are no plans of expanding the network to the little village Skogn nearby. The district heating is both supplying the offices with heat and used in heaters to heat streams in the processes instead of using steam as hot utility. The plant produces 115.7GWh of district heating and use the same amount of district heating. Most of the district heating, 64%, is produced using heat from hot processes in the plant, the rest 36% is produced in the boiler house [12].

The studied system both use and produce district heating. District heating is produced using heat of dirty condensate from the reboiler. The district heating consumers in the studied system consists of eight heaters that use district heating to

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[3] Tormod Røstad (Norske Skog Skogn mill) email contact during May 2009.

[4] Lars Johansson (Paper and Fibre Research Institute) email contact during April 2009.

[5] The term air dry refers to 90% dryness.

heat air to the dryer. The total district heating consumption within the studied system is 12.1GWh. The figures presented in this section are also summarised in Appendix 4.

3.3 Process description

Skogn is an integrated pulp and paper mill, i.e. it consists of a pulp mill and a paper mill on the same site. The main product is newsprint. The general concept is that wood chips are refined into thermo mechanical pulp (TMP) by addition of mechanical work in the refiners. The pulp is screened and bleached before it enters the paper mill. The produced TMP can be mixed with other pulps pulp and/or fillers. On the paper machine, the pulp is driven through a wire section, followed by a press section and dryer for dewatering. After the paper machine, the paper is super calendered, re-winded, wrapped and stored before shipment to the costumers [13].

In the following sections the studied system is described and the selected streams for the pinch analysis are presented. First, the pulp plant called TM2B plant is described. Later the paper plant called PM1 is described.

3.3.1 The pulp plant – TM2B

After wood and chips pre-handling operations like de-icing, debarking, chips cutting and washing, the wood chips enter the TMP plant where they are refined. The refining consists of two high consistency refining stages followed by washing in a screw press and a third low consistency refining stage. No reject refiners are used.

The TMP plant was recently rebuilt to isolate the different TMP and paper lines from each other in Skogn. The main reason for this isolation is to run TM2B and PM1 at a different pH than the rest of the mill. Due to the isolation, water streams are extensively re-circulated within the system in different stages of dilution and draining. All the effluent streams from the system needs to be cooled down to 32 °C before they are treated in the effluent treatment plant.

A schematic overview of the TMP plant with the main streams used for the pinch analysis can be seen in Figure 5. Streams are represented by arrows, those in red represent hot streams used for the analysis, whereas those in blue represent the cold streams. In the following text the main processes within the pulp production is described. The steams used in the pinch analysis are also mentioned.

Chips washing and impregnation

The chips going into the TMP plant are first washed and then drained in a screw drainer, the water used in the chip washer is recycled water from the screw drainer. This results in 4.3 l/s of effluent (stream 16). After the washing the chips are steamed and then impregnated with water. The steam demand in the steaming tower is 0.3 kg/s and it is covered with dirty steam[6] (stream 39). Before feeding the chips into the refiners, the chips are preheated with 0.9 kg/s of dirty steam (stream 40). Plug screws are installed after the steaming, impregnation and preheating, resulting in 8.1 l/s of warm effluent (stream 17).

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[6] Dirty steam is steam containing fibers.

Refining

Refining is carried out in two stage refiners. The fiber flow into the refiners is 5.5 BDkg/s[7] (6.1 ADkg/s). The first refiner has a specific energy consumption of 980 kWh/ADt of pulp and the second refiner 632 kWh/ADt. The two refiners are placed in series and produce different amounts of steam. The steam produced in each refiner is identified as forward or backward steam depending on the direction in which it flows. If the steam flows backwards, towards the inlet, it is called backward steam whereas if it the steam flows outwards, towards the periphery it is called forward steam. Bleaching of the pulp is carried out inside the refiners.

After refining, the fibers are stored at medium consistency, diluted to 8 % before washed in a screw press to 28 % consistency. The filtrate from the screw press is cleaned in a bow screen and 64 l/s of effluent (stream 9) are heat exchanged with 156 l/s of incoming white water[8] (stream 36). Some of the bow screen effluent is sent to the effluent treatment plant (stream 15) and the rest is used as make-up water for chip washing. Some of the white water is used as dilution water after the screw press and needs to be heated to 69 °C with steam (stream 37). The rest of the white water is used as dilution water in different places of the plant.

The fibers from the screw press are sent to a latency chest after which they are split into two smaller streams that are fed into the low-consistency refiners. Each low-consistency refiner has a specific energy consumption of 125 kWh/ADt. No steam is produced in the low-consistency refiners. The fibers are then collected and sent to screening. The reject is sent back to the latency chest and refined again in the low-consistency refiners. The accept is sent to the paper machine.

Steam recovery system

The backward steam from the first refiner is partly fed into the steaming and preheating towers and any excess steam is sent to the scrubber. The scrubber operation is not constant and there are no measuring instruments for the heat losses.

The rest of the steam produced in the refiners is sent to a reboiler in which the dirty steam condensates while transferring heat to 9 l/s of water (stream 38) which evaporates and transforms into clean steam that it is used in different places of the system. The condensed dirty steam, dirty condensate (stream 10), is used to preheat the feed water to the reboiler and some district heating water. The recovery degree in the reboiler is 53 %[9].

Cooling system

The refiners are cooled in two different ways: cooling of the motor (stream 11) and cooling of the bearings (stream 12). For the motor cooling, water is used to cool the air in the motor house. The water is kept at 15 °C in order to keep the motor air at approximately 80 °C. When the water has been used, it is sent to a chest and thereafter used to heat the dilution water to the refiners in TM2B and other plants.

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[7] The term bone dry refers to 100% dryness.

[8] White water is water that contains fibers.

[9] The recovery degree is a measure of how much electrical energy in the refiner is recovered in the form of clean steam.

For the bearings cooling, an oil circuit is employed. The oil that is used in the bearings exits the refiner at 60 °C and it is then stored in a chest. This oil is cooled with water down to 40 °C before re-entering the bearings.

Summary of the streams used for the pinch analysis in the TM2B plant.

A summary of the relevant streams associated with TM2B used for the pinch analysis is presented in Table 5. The streams can be identified Figure 5 by their names.

Table 5 Stream summary TM2B

Stream number	**Stream name**	**Type of stream Hot/Cold**	**Start temperature [°C]**	**Target temperature [°C]**	**Flow rate**	**Heat load [kW]**
16	Water from chip wash	Hot	60	32	4,27 l/s	499
39	Steam to Steaming	Cold	134	135	0,26 kg/s	561
40	Steam to Preheating	Cold	134	135	0,93 kg/s	2006
17	Other effluent TM2B	Hot	70	32	8,13 l/s	1275
38	Feed water to reboiler	Cold	103	111	9 l/s	296
10	Dirty condensate from reboiler	Hot	142	80	10 l/s	1885
11	Cooling of refiner motor	Hot	81	80	-	462
12	Cooling of oil to refiner	Hot	60	40	-	19
9	Water from bow screen	Hot	66	61	64 l/s	1341
36	White water from PM1	Cold	54	56	156 l/s	1341
15	Warm stream leaving TM2B	Hot	61	32	35,25 l/s	4269
37	White water continuation	Cold	56	69	93 l/s	4273

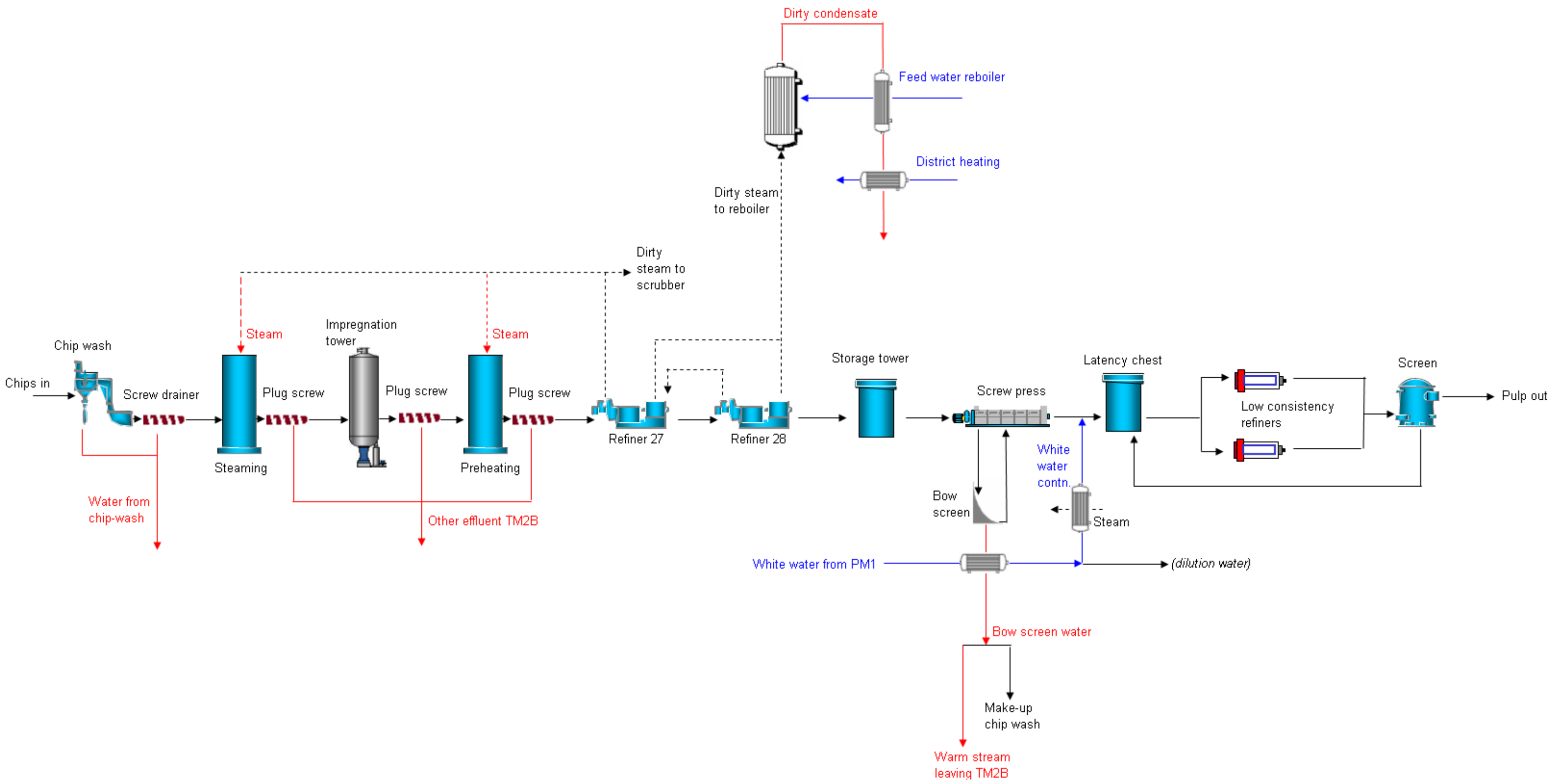

Figure 5 The TMP plant

3.3.2 The paper plant – PM1

The paper machine, PM1, is designed to produce newsprint paper with an annual production capacity of 178000 tonnes [11]. During the spring 2009 PM1 was modified due to the future introduction of fillers and DIP. The main reason for adding DIP and filler is to achieve the right paper features and lower the production cost by a reduced TMP production. The PM1 will in the future have a furnish composition of 70 % TMP, 20 % DIP and 10 % filler. The introduction of DIP and filler is done stepwise and will be complete in the end of 2009. This is the reason why the pinch analysis is made on the system without any DIP or filler. For a future scenario with DIP and fillers an analysis is carried in order to investigate the impacts on the steam production and the steam demand. The furnish composition today is shown in Table 6 and the furnish composition in the future scenario is shown in Table 7.

Table 6 The furnish composition today

PM furnish composition	
Fibre	100%
TMP	100%

Table 7 The furnish composition in the future

PM furnish composition	
Fibre	90%
TMP	70%
DIP	20%
Filler	10%

A general diagram of the paper mill can be seen in Figure 6. Before the actual paper machine there is the stock preparation which consists of storage, mixing and cleaning. After or around the paper machine there is a white water system, broke system, heat recovery system, warm water system and a cooling system. The main steps are described below.

Storage

From pulp mill TM2B the TMP is stored in a TMP tower with a volume of 245 m^3. There is also a storage tower for the broke[10]. The TMP has the consistency of 3.29 % and with a temperature of 70 °C when it exits the tower. The broke has a consistency of 3 % and a temperature of 59 °C.

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[10] Broke is paper that has been damaged in the wire, press or drying section. The broke is recovered from the paper machine and returned back to the pulping system

Mixing

From the storage towers the pulp is led into a blending chest where they are mixed. Recovered fibres from the disc filter[11] are also led to the chest. When the pulp exits the blending chest it has the consistency of 2.8 %. After the blending chest the pulp enters the machine chest, where the amount is adjusted and any surplus is returned to the blending chest. After the machine chest the stock[12] is led to the wire silo where the stock is diluted with white water to a consistency of 1 %. After the wire silo the stock is pumped out to the cyclone cleaners.

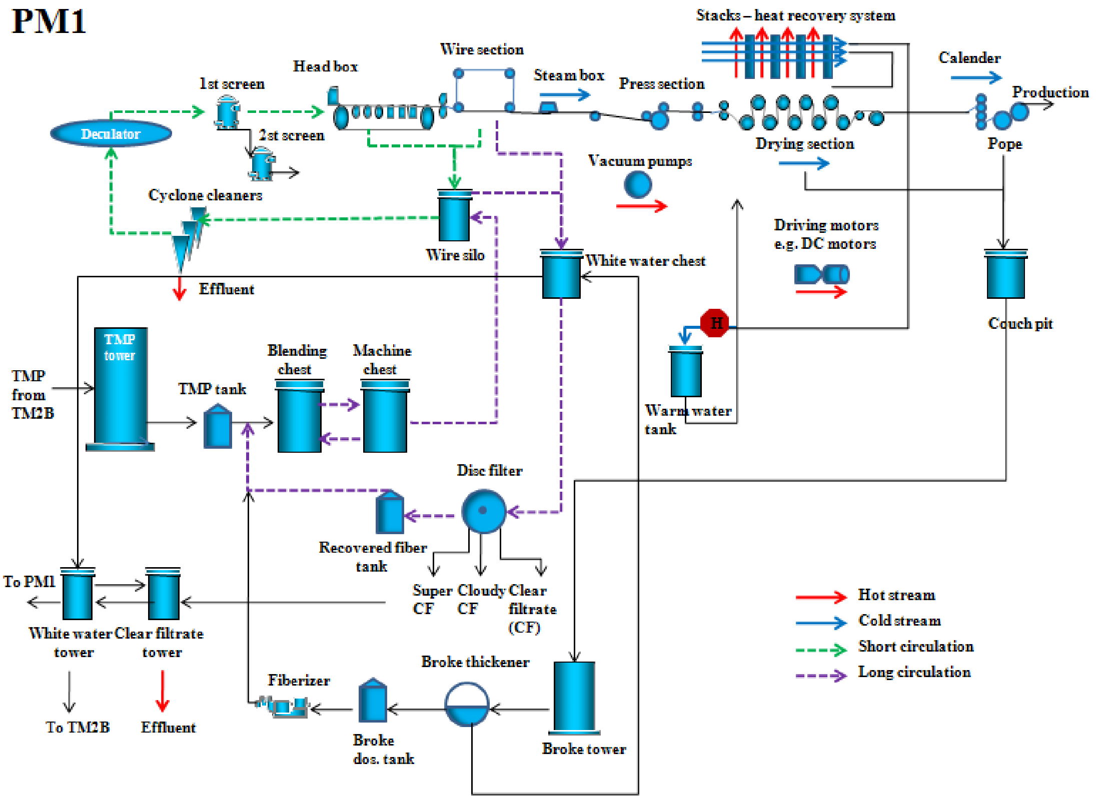

Figure 6 Process overview of PM1

Cleaning system

There are a number of stages of cyclone cleaners in the cleaning system. The cyclone cleaners are used to remove dirt and heavy particles that cannot be removed in the later screens. The particles are removed in order to prevent damage of the rolls in the paper machine. In the cyclone the stock is fed into one end and going out in the other in a continuous rotation. Dirt and heavier particles hit the wall and fall down. The particles are then collected and sent to the effluent (stream 19). After the cyclone cleaners the stock is pumped to a deculator where air is removed. Air bubbles are seen as a pollutant as they affect the drying of the paper and create unwanted paper

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[11] A disc filer is a filter that clean the white water from fibres, the clean water is usually called clear filtrate. The broke is recovered from the paper machine and returned back to the pulping system

[12] In and around the paper machine one usually use call pulp stock or furnish. This is because the original pulp has been mixed with other types of pulps and may have another composition furnish than in the TMP from the pulp mill.

formations in the paper machine. Due to the high under pressure in the deculator the stock starts to boil and then the air is possible to remove [14].

In the last step of the cleaning the stock is send to a screen, where even more pollutions are removed. The reject is screened ones more time in a reject screen after which the accept is sent back to the stock and the final reject, if any, is disposed.

Paper machine

The paper machine consists of a head box, wire section, press section, drying section and a calendar. Before the head box different chemicals are added to improve the dewatering. The stock is fed into the head box with a consistency of 1 % and a temperature of 53-54 °C. The paper machine speed is 1200 m/min.

The paper machine head box[13] has a maximum stock supply of 1182 l/s. The wire section is a hybrid former[14] and used to remove water from the layer of fibers on the wire, which is done by suctionboxes. The vacuum in the suctionboxes are produced in energy-intensive vacuums pumps which uses water for cooling. Between the wire section and the press section there is a steam box which is used to increase the temperature of the web and thereby increase the dewatering. In the steam box superheated steam (stream 34) is converted into saturated steam.

The press section has a double press and a single press. After the press section the paper dryness is between 40-45 %. The drying section consists of 49 drying cylinders. Until the half of the machine, cylinder 29, only the cylinders in the upper row have steam heating inside (stream 33). The last half, from 29 to 49, has steam heating inside all cylinders in the upper and lower row. The dryness of the paper after the dryer is 91.5 %.

The last part of the paper machine is the calendar. The calendar basically consists of four polished metal rolls, two of them with heating inside (stream 35). The paper sheet is slightly pressed between the rolls to get the right paper surface a shine. Main data for the paper machine are presented in Table 8[15].

Table 8 Main data for the paper machine from 2008

Speed design	m/min	1200
Width on pope[16]	Mm	6750
Grammage[17]	g/m^2	45(40-48.8)
Production on pope (100% eff.)	t/h	23
Paper dryness	%	91.5
PM furnish composition		
-TMP	%	100
Paper mill efficiency	%	83
Operating days per year	days/a	304
Paper production net, annual average	t/h	18

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[13] The head box is a Valmet Sym-Flo; a cross profile dilution type.

[14] The press section is a Sym former-R.

[15] Kari Norset Salater (employee at Norske Skog Skogn) emailed information about the paper machine.

[16] Width of the paper sheet on the pope (pope is a rotatable iron roll in the end of the paper machine that helps to roll the paper onto the final roll in the paper machine, called tambour).

[17] Grammage is the weight of the paper per square meter when it is saleable.

Paper production net, annual average	t/day	428
Paper production net	t/yr	129 997

White water system

When white water and the stock is fed out of the head box together they form a layer of fibers on the wire, this layer will eventually become the paper. The white water that passes through the layer is collected in the wire silo bellow the wire section. Most of the white water is recycled in the short circulation.

In the short circulation the white water is used to dilute the stock, going into the cleaning system and then fed into the head box again. The white water is recycled to reduce the mill's water consumption. When the water is recycled less heat is lost compared to if the water would have been sent to the effluent. In the short circulation the filler, if used, is usually added.

There is always a surplus of white water from the short circulation. This surplus leaves the short circulation and is either reused as colour diluter to the stock or sent to a disc filter where the fibers in the white water is recovered and added to the blending chest. The latter recovery is called the long circulation. Other products from the disc filter than the recovered fibers are clear filtrate[18], super clear filtrate[19] and cloudy clear filtrate[20].

Broke system

The paper that has been damaged in the wire, press or drying section is collected at several places in the paper machine. This paper is called broke. It is lead to a central chest called couch pit where it is mixed together with dilution water. Then it is pumped to the broke system where it is thickened, fiberized and screened. After the broke system it is returned to the blending chest.

Paper machine heat recovery system

The largest steam consumer is the drying section. The drying section is covered with a hood which prevents warm air leakage. The exhaust from the closed hood is warm air mixed with water vapour evaporated from the paper web (streams 1-8).

PM1 has four exhaust towers which works as a heat recovery systems. Each tower has a system of heat exchangers where the exhaust air is heat exchanged against indoor air, outdoor air and fresh water. The fresh water is heated from 5 °C to 40 °C (streams 28-31). The outdoor air is heated in order to balance the hall air to prevent condensation, as the hall air is very humid. If the outdoor temperature is high the incoming air does not need to be heated and is bypassed the heat exchanger. Through the heat exchangers the outdoor air is heated from 5 °C to 25 °C. After which it is heated with district heating water up to its final temperature of 35 °C (streams 24-27). The indoor air is heated in the four heat exchangers and then heated two times more first through heat exchanger with district heating water and then with a steam heater. The indoor air is heated from 42 °C to 103 °C (streams 20-23) and used as drying air

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[18] Clear filtrate is white water without most of the fibers.

[19] Super clear filtrate contains fewer fibers than clear filtrate.

[20] Cloudy filtrate contains more fibers than clear filtrate.

in the dryer. The heat recovery system of the paper machine is shown in Figure 7. The paper machine heat recovery system was modelled in the simulation program Aspen HYSYS, more information about the model can be found in Appendix 5.

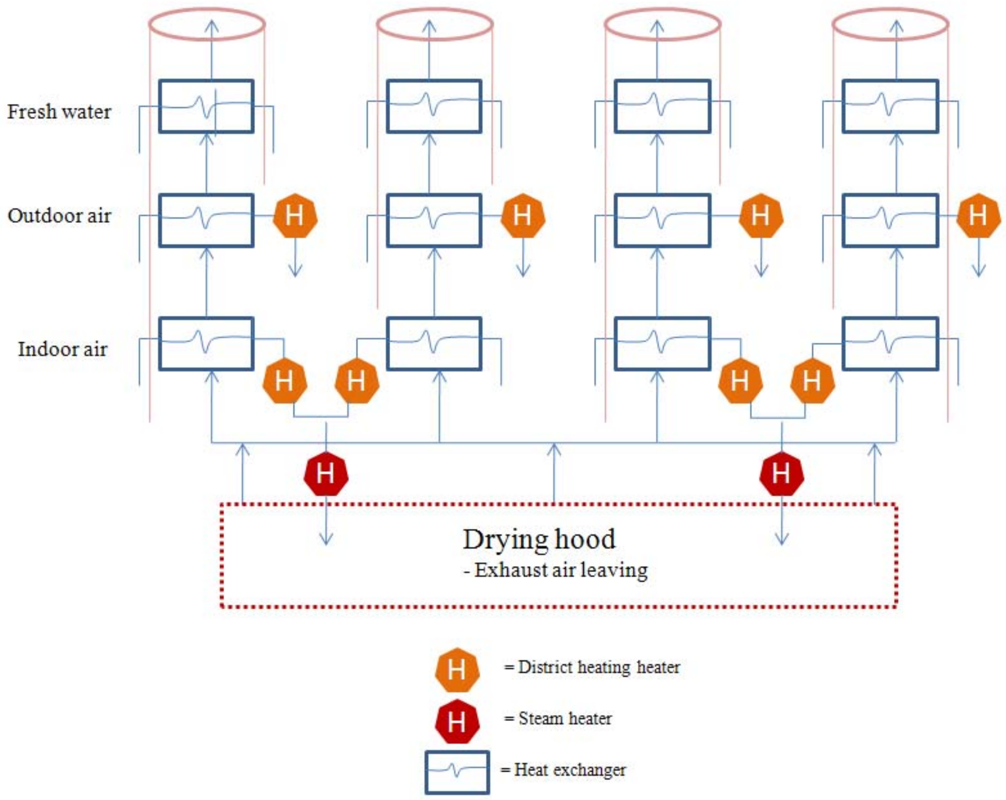

Figure 7 Paper machine heat recovery system

Warm water system

Water used in the warm water system is fresh water. The water is heated in different steps and stored in a warm water tank with a target temperature of 58 °C. First the fresh water is heated in the heat exchangers in the heat recovery system around the dryer, and then it is heated with steam to reach the target temperature (stream 32). A schematic figure of the warm water heating is shown in Figure 8.

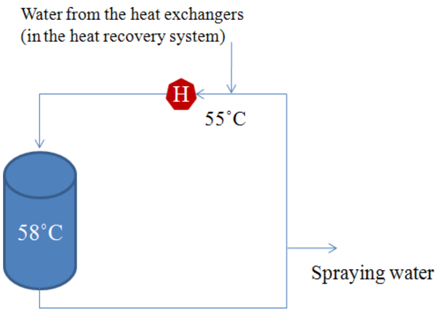

Figure 8 Heating of warm water

Warm water is used mainly in the wire and press section. In the press section it is used in the pressure cleaning showers. The showers are used to spray water onto the felt to remove dirt. After use the water is collected in the bottom of the sections and led to different chests after which it is led to the disc filter where fibers are recovered and the water is cleaned. Some of the water is reused and the rest is sent to the effluent treatment plant (stream 18).

Cooling system

There are several electric motors that drive the rolls in the paper machine. There are both AC and DC motors. The DC motors are the motors that need additional cooling (stream 14). The motors are cooled by air.[21]

In the paper machine there is a demand for vacuum at different places to facilitate the dewatering of the paper. There are several pumps that are producing the vacuum and these pumps also need cooling. The pumps are cooled using water (some of hot stream 13).

At the effluent treatment plant the incoming effluents have to be cooled down to 32 ˚C otherwise the biological cleaning will not work.

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[21] Kertil Røe (employee at Norske Skog Skogn, in charge of the electric motors at the plant) interviewed 17 March 2009.

Streams used in the pinch analysis

A summary of the relevant streams used for the pinch analysis is presented in Table 9.

Table 9 Stream summary PM1

Stream number	Stream name	Type of stream Hot/Cold	Start temperature [˚C]	Target temperature [˚C]	Flow rate		Heat load [kW]
1	Air from dryer, stream 1	Hot	90	55	19.3	kg/s	741
2	Air from dryer, stream 1 condensation	Hot	55	51	19.3	kg/s	1093
3	Air from dryer, stream 2	Hot	90	55	19.3	kg/s	741
4	Air from dryer, stream 2 condensation	Hot	55	48	19.3	kg/s	1732
5	Air from dryer, stream 3	Hot	90	55	19.3	kg/s	743
6	Air from dryer, stream 3 condensation	Hot	55	48	19.3	kg/s	1791
7	Air from dryer, stream 4	Hot	90	55	19.3	kg/s	741
8	Air from dryer, stream 4 condensation	Hot	55	46	19.3	kg/s	2042
20	Air to dryer, steam 1	Cold	42	103	11	kg/s	688
21	Air to dryer, steam 2	Cold	42	103	11	kg/s	688
22	Air to dryer, stream 3	Cold	42	103	9.8	kg/s	608
23	Air to dryer, stream 4	Cold	42	103	9.8	kg/s	608
24	Air for mix, steam 1	Cold	5	35	20	kg/s	594
25	Air for mix, stream 2	Cold	5	35	20	kg/s	594
26	Air for mix, stream 3	Cold	5	35	20	kg/s	594
27	Air for mix, stream 4	Cold	5	35	20	kg/s	594
28	Fresh water, stream 1	Cold	5	33	11.8	kg/s	1385
29	Fresh water, stream 2	Cold	5	42	13.2	kg/s	2029
30	Fresh water, stream 3	Cold	5	44	12.6	kg/s	2075
31	Fresh water, stream 4	Cold	5	45	14	kg/s	2323
32	Warm water in warm water circuit	Cold	55	58	-		1520
33	Dryer (steam demand)	Cold	134	135	7.3	kg/s	15900
34	Steam box (steam demand)	Cold	134	135	0.8	kg/s	1890
35	Calender (steam demand)	Cold	134	135	0.4	kg/s	945
13	Other cooling	Hot	45	40	-		7963
14	Cooling of DC motors in PM1	Hot	71	70	-		906
18	Warm clear filtrate from PM1 to effluent	Hot	55	32	24	l/s	2287
19	Effluent from PM1	Hot	56	32	2	l/s	201

4 Present situation

In the following sections the present energy situation at the mill is presented and compared with a maximum energy recovery network. Moreover, the heat exchanger network is illustrated and the major pinch violations are identified.

4.1 Characteristics and comparison with a MER network

From a large set of stream data representing the current situation at the mill[22], 40 streams were selected and analysed. These streams represent the streams in the studied system that either demand heating or cooling. Of these 40 streams, 19 represent streams that need cooling, i.e. hot streams, and 21 streams that need heating, i.e. cold streams.

The minimum allowed temperature difference set for each stream is in agreement with previous studies [6] in TMP mills. Different ΔT_{min} were assigned to different kind of fluids, based on their individual heat transfer properties. A summary of the ΔT_{min} used for every kind of stream can be seen in Table 10. The relevant information about the streams is summarized in Table 11.

Table 10 Minimum temperature difference for the pinch analysis

Type of stream	ΔTmin/2 [˚C]
Clean water	2.5
Dirty water	3.5
Steam from refiner	2
Clean steam	1
Air	8
Oil	4

The grand composite curve and the composite curves of the studied system are displayed in Figure 9 and Figure 10, respectively. From the grand composite curve it can be seen that the theoretical minimum demands of hot and cold utilities are 24.0 MW and 13.2 MW, respectively. These figures can be compared to the existing heating and cooling demands 28.7 MW and 17.9 MW (Table 12). As can be expected, the existing utility demand is larger than the theoretical minimum demand and the difference between the two illustrates the possibility for utility savings through retrofit of the studied system.

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[22] Read more about the data gathering process and the different data sources in section 1.3.

Table 11 Stream summary

Number of stream	Name	Type	Tstart °C	Ttarget °C	Q kW	ΔT °C
1	Air from dryer 1	Hot	90	55	741	8
2	Air from dryer 1c	Hot	55	51	1093	8
3	Air from dryer 2	Hot	90	55	741	8
4	Air from dryer 2c	Hot	55	48	1732	8
5	Air from dryer 3	Hot	90	55	743	8
6	Air from dryer 3c	Hot	55	48	1791	8
7	Air from dryer 4	Hot	90	55	741	8
8	Air from dryer 4c	Hot	55	46	2042	8
9	Bowscreen water	Hot	66	61	1341	3.5
10	Dirty condensate	Hot	142	95	1885	3.5
11	Cooling of refiner motor air	Hot	81	80	462	8
12	Cooling of refiner - oil circuit	Hot	60	40	19	4
13	Other cooling	Hot	45	40	7963	2.5
14	Cooling of DC motors in PM1	Hot	71	70	906	8
15	Warm stream leaving TM2B	Hot	61	32	4269	3.5
16	Water from chip wash	Hot	60	32	499	3.5
17	Other effluent from TM2B	Hot	70	32	1275	3.5
18	Warm clear filtrate from chest (PM1)	Hot	55	32	2287	3.5
19	Effluent from PM1	Hot	56	32	201	3.5
20	Air to dryer	Cold	42	103	688	8
21	Air to dryer	Cold	42	103	688	8
22	Air to dryer	Cold	42	103	608	8
23	Air to dryer	Cold	42	103	608	8
24	Air for mix	Cold	5	35	594	8
25	Air for mix	Cold	5	35	594	8
26	Air for mix	Cold	5	35	594	8
27	Air for mix	Cold	5	35	594	8
28	Fresh water	Cold	5	33	1385	2.5
29	Fresh water	Cold	5	42	2029	2.5
30	Fresh water	Cold	5	44	2075	2.5
31	Fresh water	Cold	5	45	2323	2.5
32	Warm water	Cold	55	58	1520	2.5
33	Dryer	Cold	134	135	15900	1
34	Steambox	Cold	134	135	1890	1
35	Calender	Cold	134	135	945	1
36	White water from PM1	Cold	54	56	1341	3.5
37	White water continuation.	Cold	56	69	4273	3.5
38	Feed water	Cold	103	111	296	3.5
39	Steaming	Cold	134	135	561	2
40	Preheating	Cold	134	135	2006	2

Table 12 Existing and minimum heating demand and cooling demand

Heating demand and cooling demand [MW]

	EXISTING	MINIMUM	POTENTIAL FOR SAVINGS
Hot utility consumption	28.7	24.0	4.7
Cold utility consumption	17.9	13.2	4.7

The pinch temperature of the studied system is 57.5 °C, which means that the system has a deficit of heat above and an excess of heat below 57.5 °C.

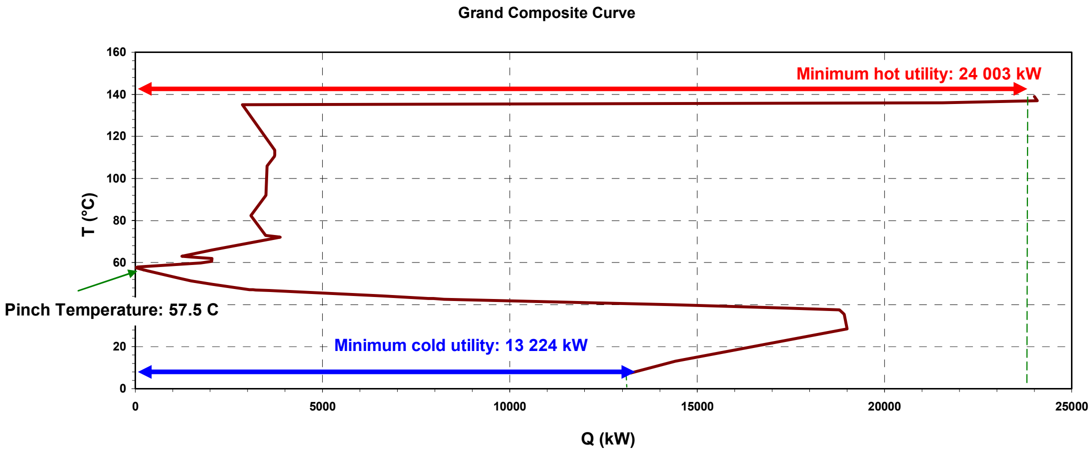


Figure 9 Grand composite curve

The minimum heating and cooling demands are also illustrated by the composite curves in Figure 10. The potential for internal heat exchange is represented by the grey arrow section and equals 17.5 MW. As can be expected, the internal heat exchange in the existing system is smaller (-4.6 MW). This number is presented in the following section where the existing heat exchanger network is illustrated.

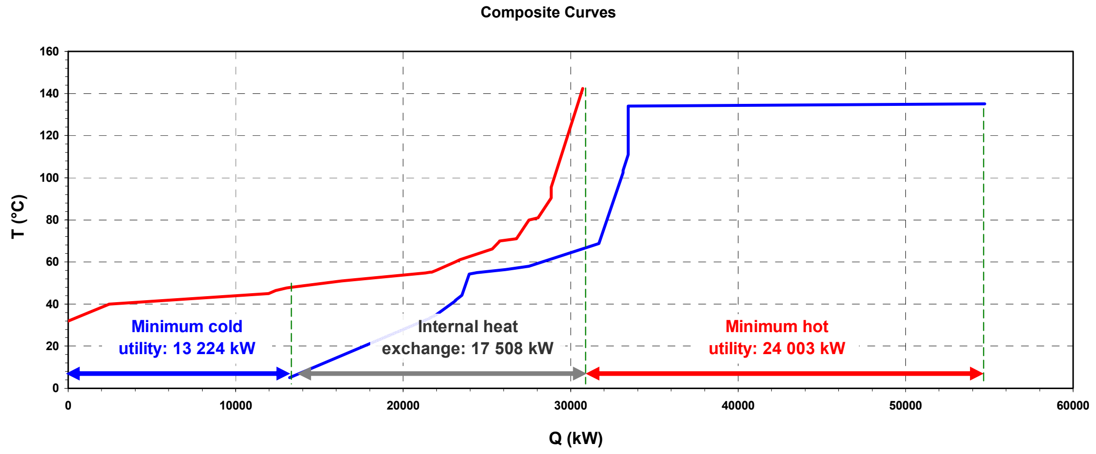


Figure 10 Composite curves

4.2 Existing heat exchanger network

In practice, the heat exchanger network does not recover as much heat internally as is theoretically possible. This is due to the fact that different pinch violations are present in the system. The existing heat exchanger network for the system studied in this thesis is presented in Figure 11. Blue boxes represent coolers, yellow boxes represent heaters and the grey, connected boxes represent internal heat exchangers, in which 12.9 MW are transferred.

4.3 Pinch violations in the existing heat exchanger network

In the existing heat exchanger network, two kinds of pinch violations are present: cooling above the pinch and transferring heat through the pinch. Figure 12 illustrates the cooling of the refiners' motors (stream 11) and the cooling of the DC motors (stream 14). These streams are well above the pinch and are being cooled, clear pinch violations.

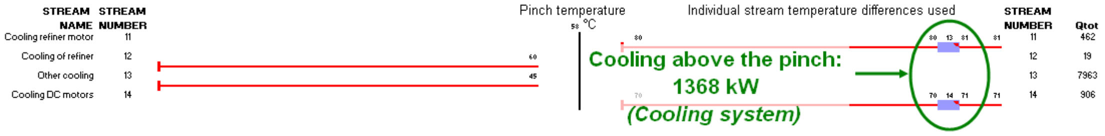


Figure 11 Pinch violations: Cooling above the pinch in the cooling system.

Additionally, other coolers are partially cooling above the pinch. This means that a hot stream is cooled from a temperature above the pinch to a temperature below the pinch. The part of the cooling that is done below the pinch is not a pinch violation but the part of the cooling above the pinch is a pinch violation. These pinch violations are illustrated in Figure 13. For cooling of the warm stream leaving TM2B (stream 15), 4.3 MW of cold utility are used but 0.013 MW of cooling is done above the pinch. The rest of the cooling below the pinch does not represent a pinch violation. For the other effluent from TM2B (stream 17), 1.3 MW of cold utility is used and 0.3 MW of this cooling is done above the pinch.

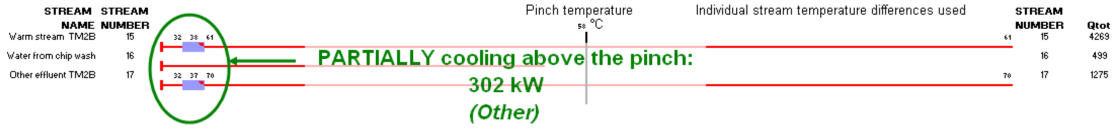


Figure 12 Pinch violations: Partially cooling above the pinch in other effluent streams.

Heat is also transferred through the pinch. This type of pinch violation is illustrated in Figure 14. This type of pinch violation occurs in the paper machine heat recovery system where heat is transferred from the air from the dryer (streams 1, 3, 5, 7) that it is above the pinch to air to dryer (streams 20-23), air for mix (streams 24-27) and fresh water (streams 28-31). These streams are completely or partially below the pinch. In this heat recovery system, 2.1 MW are transferred through the pinch.

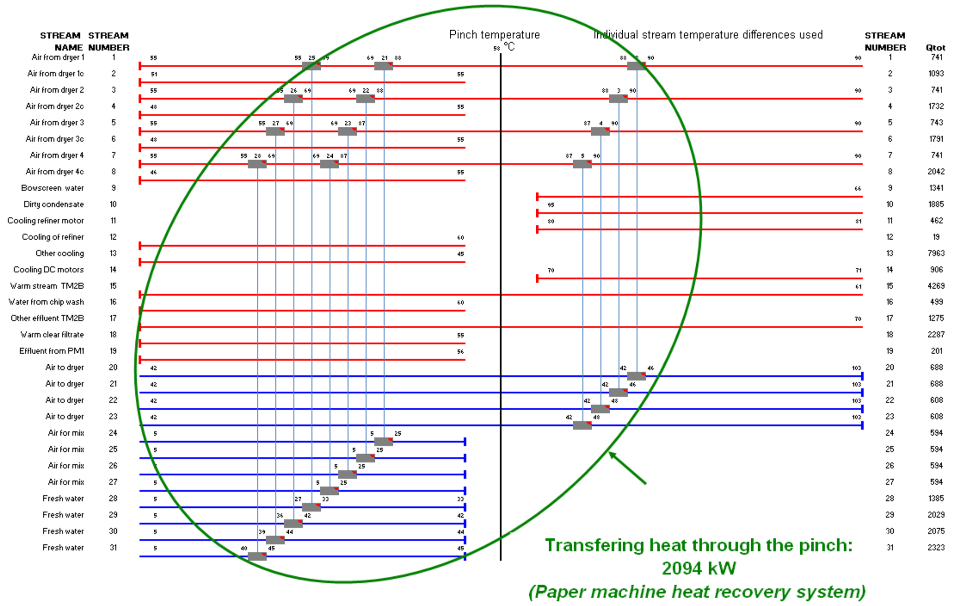


Figure 13 Pinch violations: Transferring heat through the pinch in paper machine heat recovery system.

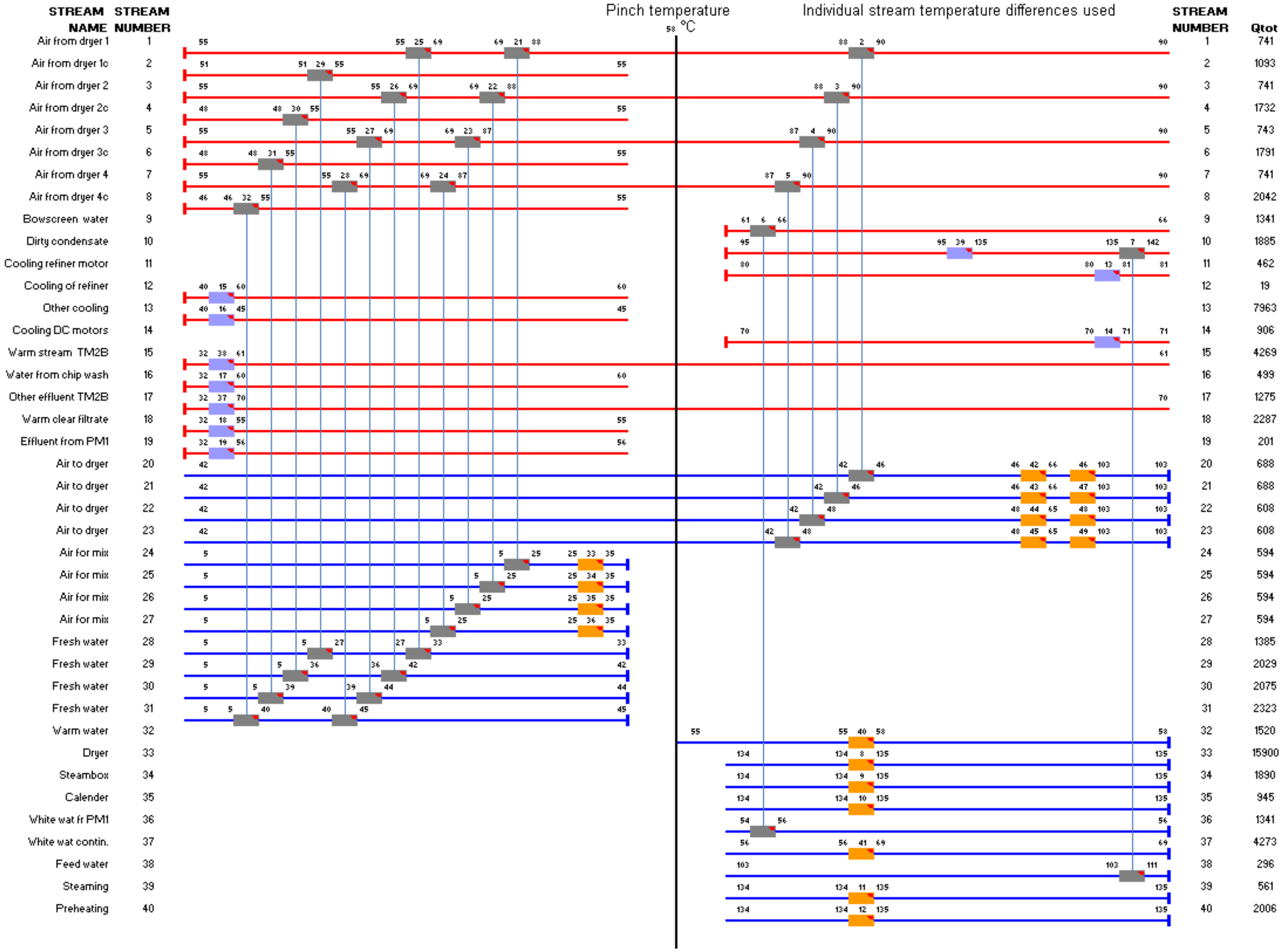
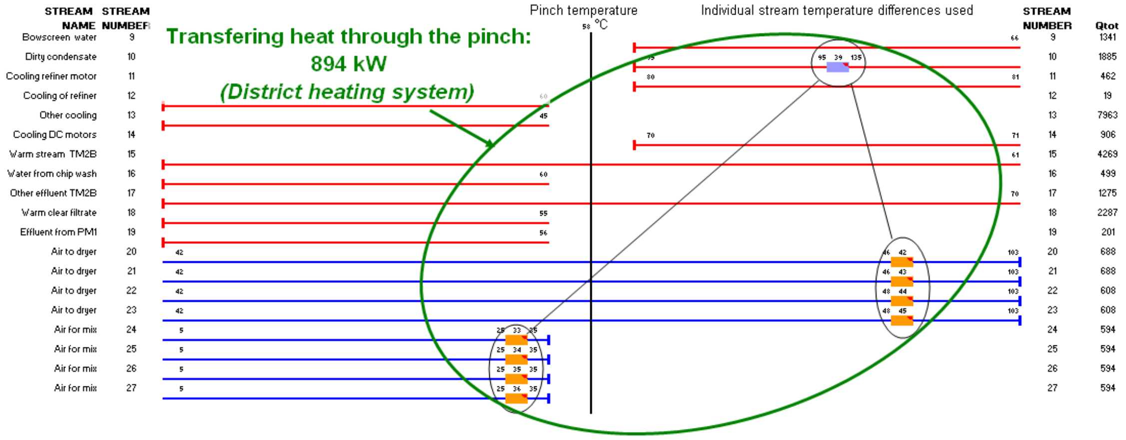


Figure 14 Network representation

Finally, heat is also transferred through the pinch in the district heating system. This system is a common system for the entire mill and was challenging to model to use it in the pinch analysis. A description of the way the district heating was treated and the assumptions that were made is presented in Appendix 6.

In the pinch analysis it was considered that the dirty condensate (stream 10) was heating the air for mix (streams 24-27) and air to dryer (streams 20-23) rather than heating district heating water. However, in the network representation the production and consumption of district heating is represented as coolers and heaters respectively to avoid overloading the figure. The production of district heating is represented by a cooler in the dirty condensate (stream 10). The consumption of district heating is represented as heaters in the air for mix (streams 24-27) and air to dryer (streams 20-23).

Since the district heating water is heated by the dirty condensate which is above the pinch and it is consumed by streams that are partially or completely below the pinch, heat is transferred through the pinch which corresponds to 0.9 MW of pinch violations. This is illustrated in Figure 15.



STREAM NAME	STREAM NUMBER	Qtot
Bowscreen water	9	1341
Dirty condensate	10	1885
Cooling refiner motor	11	462
Cooling of refiner	12	19
Other cooling	13	7963
Cooling DC motors	14	906
Warm stream TM2B	15	4269
Water from chip wash	16	499
Other effluent TM2B	17	1275
Warm clear filtrate	18	2287
Effluent from PM1	19	201
Air to dryer	20	688
Air to dryer	21	688
Air to dryer	22	608
Air to dryer	23	608
Air for mix	24	594
Air for mix	25	594
Air for mix	26	594
Air for mix	27	594

Figure 15 Pinch violations: Transferring heat through the pinch in district heating system.

Summary of pinch violations in the existing heat exchanger networks

The pinch violations are summarized in Table 13. It can be seen that the biggest source of pinch violations is the paper machine heat recovery system which stands for 45% of all the pinch violations. Secondly, the cooling of the DC motors and the refiners motors with 29% and thirdly the district heating system with 19%. The rest of the streams accounts only for 6% of the total pinch violations. Overall, 3 MW are transferred through the pinch and 1.7 MW are cooling above the pinch.

Table 13 Summary of pinch violations

Number of pinch violation	**Stream name**	**Stream number**	**Stream name**	**Stream number**	**Qvvx**	**Q through pinch**	**Cooling above**	**Heating below**	**% Total pinch violations**
	Hot stream		**Cold stream**		**MW**	**MW**	**MW**	**MW**	**%**
AIR FROM DRYER HEAT RECOVERY SYSTEM									
1	Air from dryer	1, 3, 5, 7	Air for mix	24, 25, 26, 27	1.6	1.6	0.0	0.0	34
2	Air from dryer	1, 3, 5, 7	Fresh water	28, 29, 30, 31	1.2	0.3	0.0	0.0	6
3	Air from dryer	1, 3, 5, 7	Air to dryer	20, 21, 22, 23	0.2	0.2	0.0	0.0	5
									45
COOLING									
4	Cooling DC motors	14	Cooler	-	0.9	0.0	0.9	0.0	19
5	Cooling refiner motor	11	Cooler	-	0.5	0.0	0.5	0.0	10
									29
DISTRICT HEATING SYSTEM									
6	District heating heater	-	Air for mix	24, 25, 26, 27	0.8	0.8	0.0	0.0	17
7	District heating heater	-	Air to dryer	20, 21, 22, 23	0.8	0.1	0.0	0.0	2
									19
OTHER									
8	Other effluent TM2B	17	Cooler	-	1.3	0.0	0.3	0.0	6
9	Warm stream TM2B	15	Cooler	-	4.3	0.0	0.0	0.0	0
									6
					TOTAL	3.0	1.7	0.0	
							4.7		**100**

According to the minimum and real utilities consumption the maximum potential for savings of hot utility is 4.7 MW, this is the same as the total amount of pinch violations. In practice however, this potential is somehow limited by the way the cooling of the refiners' motors and the DC motors is carried out. As this cooling is considered unchangeable, the potential for savings is decreased which means that a constant pinch violation of 1.4 MW has been accepted. Thus, in the retrofit proposals in Chapter 5, the maximum potential for savings of hot utility is set to 3.3 MW.

The maximum potential for savings that can be achieved by solving the previously mentioned pinch violations in the heat exchanger network is presented in Table 14. It is interesting to notice that nearly all the pinch violations were found in only two auxiliary systems: the paper machine heat recovery system (64%) and the district heating system (27%).

Table 14 Potential for savings in the existing heat exchanger network

Number of pinch violation	**Stream name**	**Stream number**	**Stream name**	**Stream number**	**Qvvx**	**Q through pinch**	**Cooling above**	**Heating below**	**% Total pinch violations**
	Hot stream		**Cold stream**		**MW**	**MW**	**MW**	**MW**	**%**
AIR FROM DRYER HEAT RECOVERY SYSTEM									
1	Air from dryer	1, 3, 5, 7	Air for mix	24, 25, 26, 27	1.6	1.6	0.0	0.0	48
2	Air from dryer	1, 3, 5, 7	Fresh water	28, 29, 30, 31	1.2	0.3	0.0	0.0	9
3	Air from dryer	1, 3, 5, 7	Air to dryer	20, 21, 22, 23	0.2	0.2	0.0	0.0	7
									64
DISTRICT HEATING SYSTEM									
6	District heating heater	-	Air for mix	24, 25, 26, 27	0.8	0.8	0.0	0.0	24
7	District heating heater	-	Air to dryer	20, 21, 22, 23	0.8	0.1	0.0	0.0	3
									27
OTHER									
8	Other effluent TM2B	17	Cooler	-	1.3	0.0	0.3	0.0	9
9	Warm stream TM2B	15	Cooler	-	4.3	0.0	0.0	0.0	0
									9
					TOTAL	3.0	0.3	0.0	
							3.3		**100**

5 Retrofits possibilities

In the following section a set of different possible retrofit solutions is presented. The proposals vary in complexity and energy-savings and address the system shortcomings from different perspectives. The first three proposals, Retrofit 1-3 focus on solving the pinch violations presented in the previous chapter by improving the heat exchanger network whereas the other retrofit suggestions, Retrofit 4 and 5, keep the heat exchanger network nearly unchanged but achieve energy-saving through alternative process integration solutions. These alternative retrofit solutions are preheating of certain streams and integration of a heat pump.

5.1 Retrofit 1 – light

Analysing the major pinch violations in the existing system (see section 4.3) the paper machine heat recovery system was identified as the largest pinch violation. This heat recovery system is described in section 3.3.2 and is schematically represented as the three gray heat exchangers in Figure 16. In the figure only one of the four towers is presented for simplicity reasons[23].

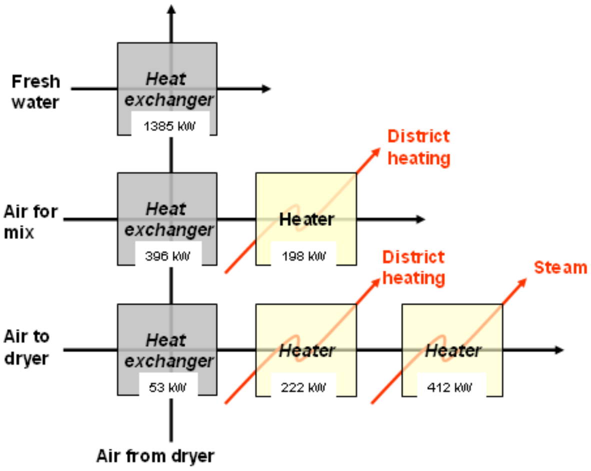


Figure 16 Paper machine heat recovery system (three gray heat exchangers), existing configuration

As previously described, three different retrofit proposal based on elimination of pinch violations with increasing degree of complexity are investigated. For this first retrofit, Retrofit 1 – light, it was assumed that the heat exchangers in the paper machine heat recovery system were unchangeable. Even with this limitation it is possible to find an improved configuration of the heat exchanger network by modifying four district heating heaters after the heat recovery system (replace them with four heat exchangers) and by adding two new heat exchangers. The modifications proposed in Retrofit 1- light are:

---

[23] The four tours of the paper machine heat recovery system were modelled in Aspen HYSYS. The main assumptions for the simulations as well as the results are shown in Appendix 5.

1. The stream of warm, clear filtrate from PM1 (stream 18) which is currently sent directly to the effluent treatment plant is used to heat the air for mix. (streams 24-27) This decreases the use of district heating.
2. Decreasing the use of district heating will in turn give the possibility to use heat from the dirty condensate (stream 10) that is currently producing district heating to heat some white water which was previously heated with steam (stream 37)[24].
3. Finally, the effluent from TM2 (stream 17) can be used to heat some warm water before sending it to the effluent treatment plant (stream 32). The warm water was previously heated with steam.

The retrofitted heat exchanger network for this configuration is shown in Figure 17 and the paper machine heat recovery system configuration is shown in Figure 18. In Table 15 the pinch violations eliminated are presented:

Table 15 Pinch violations elimination in Retrofit 1 - light

Number of pinch violation	**Stream name**	**Stream number**	**Stream name**	**Stream number**	**Qvvx**	**Q through pinch**	**Cooling above**	**Heating below**	**Comment**
	Hot stream		**Cold stream**		**MW**	**MW**	**MW**	**MW**	
DISTRICT HEATING SYSTEM									
6	District heating heater	-	Air for mix	24, 25, 26, 27	0.8	0.8	0.0	0.0	Eliminated
OTHER									
8	Other effluent TM2B	17	Cooler	-	1.3	0.0	0.3	0.0	Eliminated
							1.1		

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[24] The district heating system is a common system for different paper lines outside the system boundaries. It was therefore necessary to treat it in a simplified way. An explanation of the way this was done can be found in Appendix 5.

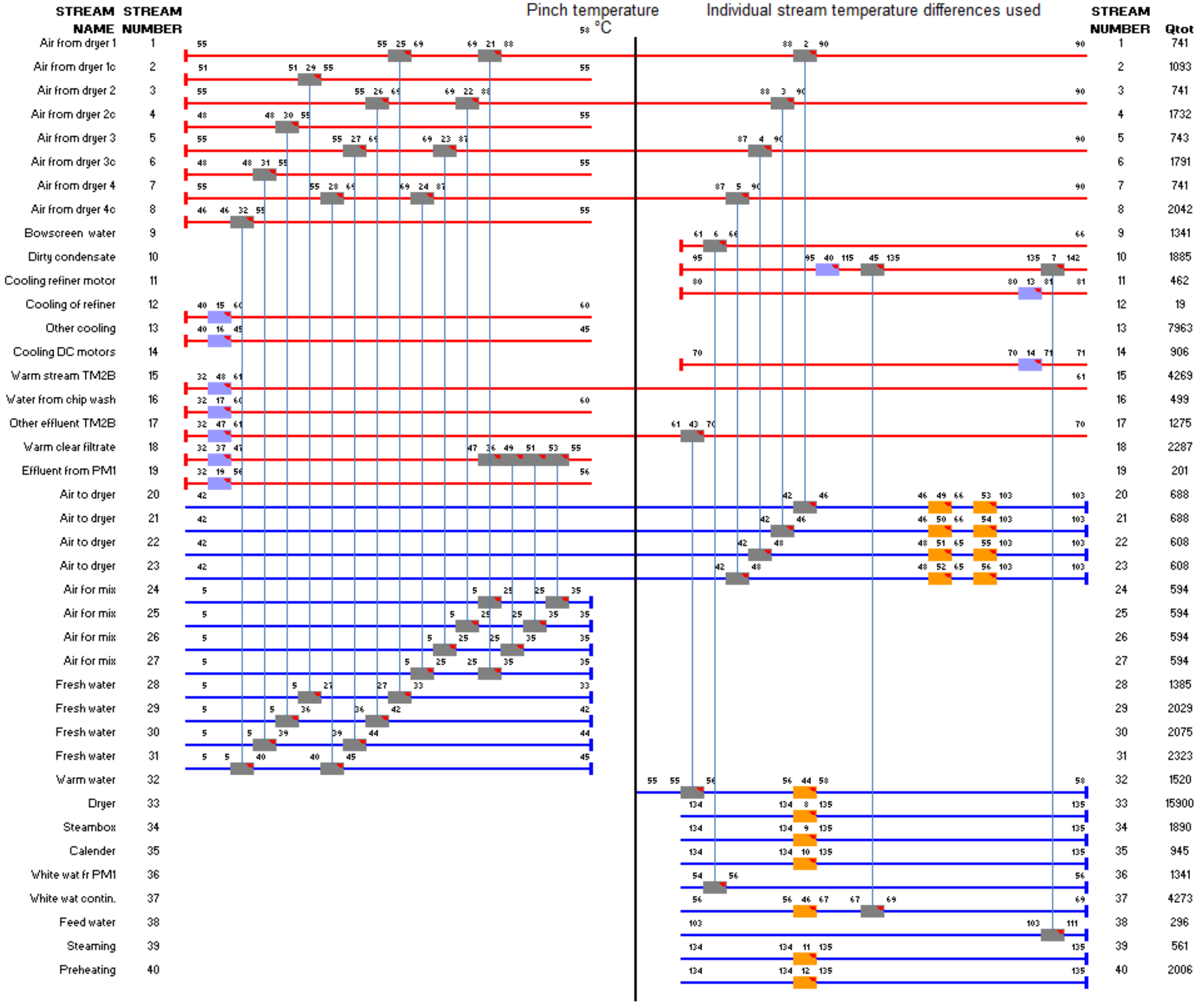

Figure 17 Network representation. Retrofit 1

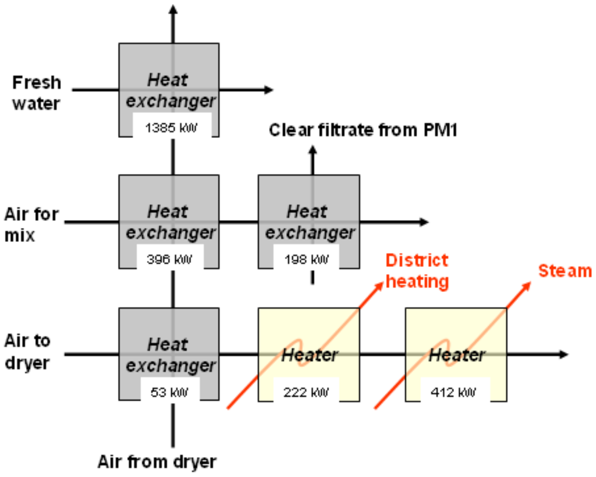

Figure 18 Paper machine heat recovery system (three gray heat exchangers), Retrofit 1

The heat exchanger network configuration in Retrofit 1 – light has a hot utility demand of 27.6 MW. This can be compared with the original network heat demand of 28.7 MW. This indicates a steam saving of 1.1 MW for the retrofit, equal to 33% of the savings of a MER network (3.3 MW). The results are summarised in Table 16.

Table 16 Summary results retrofit 1 - light

Heat exchanger network configuration	**Hot utility demand [MW]**	**Heat recovered [MW]**	**Savings compared to MER [%]**
Existing network	28.7	0.0	0
Retrofit 1	27.6	1.1	33

5.2 Retrofit 2 – medium

In the second retrofit proposal, Retrofit 2 - medium, it was assumed that the paper machine heat recovery system could be slightly modified by using the same streams but in a different configuration. In this case the air from the dryer (streams 1-8) exchanges more heat with the air to dryer (streams 20-23) and less heat with the air for mix (streams 24-27). Also the order of the heat exchangers in the heat recovery system is changed as shown in Figure 19.

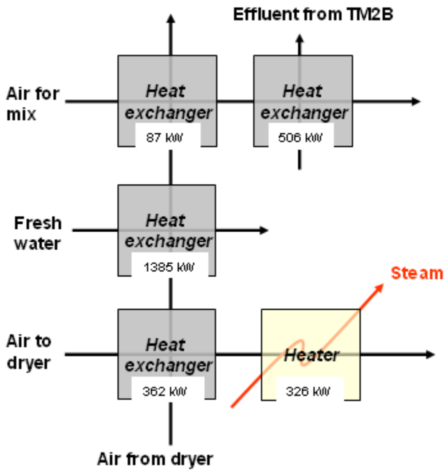

Figure 19 Paper machine heat recovery system (three gray heat exchangers), Retrofit 2

The modifications proposed in Retrofit 2 - medium are:

1. The paper machine heat recovery system is modified as illustrated in Figure 19. The air to dryer (streams 20-23), is heated further than before with the air from the dryer (streams 1, 3, 5, 7), and consequently does not require heating with district heating anymore.
2. The decreased use of district heating will in turn give the possibility to use more heat from the dirty condensate (stream 10) (currently producing district heating) to heat white water (stream 37) even further than in Retrofit 1.[25]
3. Finally, as in Retrofit 1, the effluent from TM2 (stream 17) is used to heat warm water (stream 32) before it is sent to the effluent treatment plant.

The retrofitted heat exchanger network for this configuration is shown in Figure 20. The modifications in the paper machine heat recovery system include modifying four heaters (replace them with four heat exchangers) and adding capacity in four heat exchangers. Additionally two new heat exchangers are needed. In Table 17 the pinch violations eliminated are presented.

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[25] The way that the district heating system was treated in this thesis is described in Appendix 5.

Table 17 Pinch violations elimination in Retrofit 2 - medium

Number of pinch violation	Stream name	Stream number	Stream name	Stream number	Qvvx	Q through pinch	Cooling above	Heating below	Comment
	Hot stream		Cold stream		MW	MW	MW	MW	
PAPER MACHINE HEAT RECOVERY SYSTEM									
1	Air from dryer	1, 3, 5, 7	Air for mix	24, 25, 26, 27	1.6	1.6	0.0	0.0	Reduced by 1.6 MW
2	Air from dryer	1, 3, 5, 7	Fresh water	28, 29, 30, 31	1.2	0.3	0.0	0.0	Increased by 0.4 MW
3	Air from dryer	1, 3, 5, 7	Air to dryer	20, 21, 22, 23	0.2	0.2	0.0	0.0	Increased by 0.1 MW
DISTRICT HEATING SYSTEM									
6	District heating heater	-	Air for mix	24, 25, 26, 27	0.8	0.8	0.0	0.0	Eliminated
7	District heating heater	-	Air to dryer	20, 21, 22, 23	0.8	0.1	0.0	0.0	Eliminated
OTHER									
8	Other effluent TM2B	17	Cooler	-	1.3	0.0	0.3	0.0	Eliminated
9	Warm stream TM2B	15	Cooler	-	4.3	0.0	0.0	0.0	Eliminated
							2.2		

In this case, the retrofitted heat exchanger network has a hot utility demand of 26.4 MW which can be compared with the original network´s heat demand of 28.7 MW. Thus the steam saving achieved by the retrofit is 2.2 MW, corresponding to 68% of the savings of a MER network (3.3 MW). The results are summarised in Table 18.

Table 18 Summary results Retrofit 2 - medium

Heat exchanger network configuration	Hot utility demand [MW]	Heat recovered [MW]	Savings compared to MER [%]
Existing network	28.7	0.0	0
Retrofit 2	26.4	2.2	68

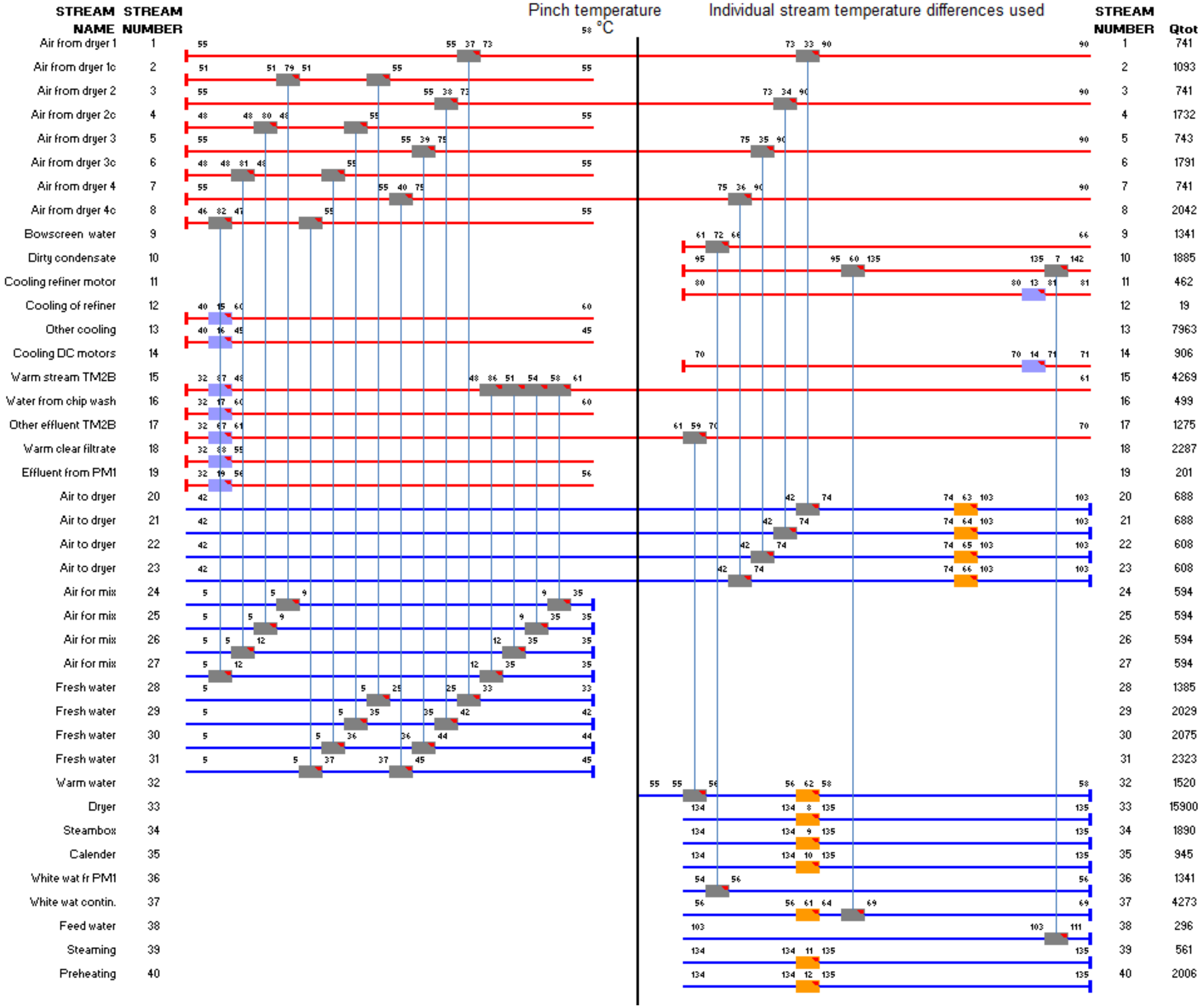

Figure 20 Network representation. Retrofit 2.

5.3 Retrofit 3 – deluxe

The third retrofit proposal, Retrofit 3 – deluxe, is the most modified network. Here, it was assumed that the paper machine heat recovery system can be modified completely, using streams from other parts of the system if appropriate. For this retrofit the proposed modifications are:

1. In the paper machine heat recovery system, the heat exchange to fresh water (streams 28-31) remains unmodified, but the heating of air for mix (streams 24-27) and air to dryer (streams 20-23) is achieved using other streams.
2. The rest of the heat available in the air from the dryer (streams 1, 3, 5, 7) is used to heat white water (stream 37) which was previously heated with steam.
3. The warm stream leaving TM2B (stream 15) which is currently sent to the effluent treatment plant is used to heat the air for mix (streams 24-27) and air to dryer (streams 20-23).
4. As in the existing network, the air to dryer (streams 20-23) demands further heating which is covered by steam. The steam demand in these heaters is larger than in the existing network.
5. As no district heating is used, it is possible to use the heat from the dirty condensate (stream 10) (currently producing district heating) to heat white water (stream 37) as in Retrofit 2.[26]
6. Finally, as in Retrofit 1, the effluent from TM2 (stream 17) is used to heat warm water (stream 32) before it is sent to the effluent treatment plant.

The configuration of the paper machine heat recovery system for Retrofit 3 – deluxe, is shown in Figure 21 and the complete retrofitted heat exchanger network is shown in Figure 22. The modifications in the paper machine heat recovery system include modifying four heaters (replace them with four heat exchangers) and buying eight heat exchangers. Additionally two new heat exchangers are needed. In Table 19 the pinch violations eliminated are presented:

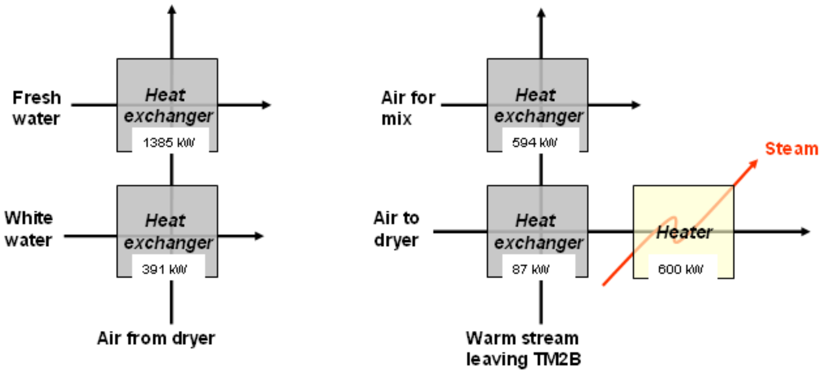

Figure 21 Paper machine heat recovery system (two gray heat exchangers), Retrofit 3

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[26] The way that the district heating system was treated in this thesis is described in Appendix 5.

Table 19 Pinch violations elimination in Retrofit 3 - deluxe

Number of pinch violation	Stream name	Stream number	Stream name	Stream number	Qvvx	Q through pinch	Cooling above	Heating below	Comment
	Hot stream		**Cold stream**		**kW**	**kW**	**kW**	**kW**	
PAPER MACHINE HEAT RECOVERY SYSTEM									
1	Air from dryer	1, 3, 5, 7	Air for mix	24, 25, 26, 27	1.6	1.6	0.0	0.0	Eliminated
2	Air from dryer	1, 3, 5, 7	Fresh water	28, 29, 30, 31	1.2	0.3	0.0	0.0	Increased by 0.09 MW
3	Air from dryer	1, 3, 5, 7	Air to dryer	20, 21, 22, 23	0.2	0.2	0.0	0.0	Decreased by 0.18 MW
DISTRICT HEATING SYSTEM									
6	District heating heater	-	Air for mix	24, 25, 26, 27	0.8	0.8	0.0	0.0	Eliminated
7	District heating heater	-	Air to dryer	20, 21, 22, 23	0.8	0.1	0.0	0.0	Eliminated
OTHER									
8	Other effluent TM2B	17	Cooler	-	1.3	0.0	0.3	0.0	Eliminated
9	Warm stream TM2B	15	Cooler	-	4.3	0.0	0.0	0.0	Eliminated
							2.9		

In this third retrofit, the heat exchanger network has a hot utility demand of 25.8 MW which can be compared to the heat demand of the existing network of 28.7 MW. Thus the steam saving achieved by the retrofit is 2.9 MW, equal to 87% of the savings of a MER network (3.3 MW). The results are summarised in Table 20.

Table 20 Summary results Retrofit 3 – deluxe

Heat exchanger network configuration	Hot utility demand [MW]	Heat recovered [MW]	Savings compared to MER [%]
Existing network	28.7	0.0	0
Retrofit 3	25.8	2.9	87

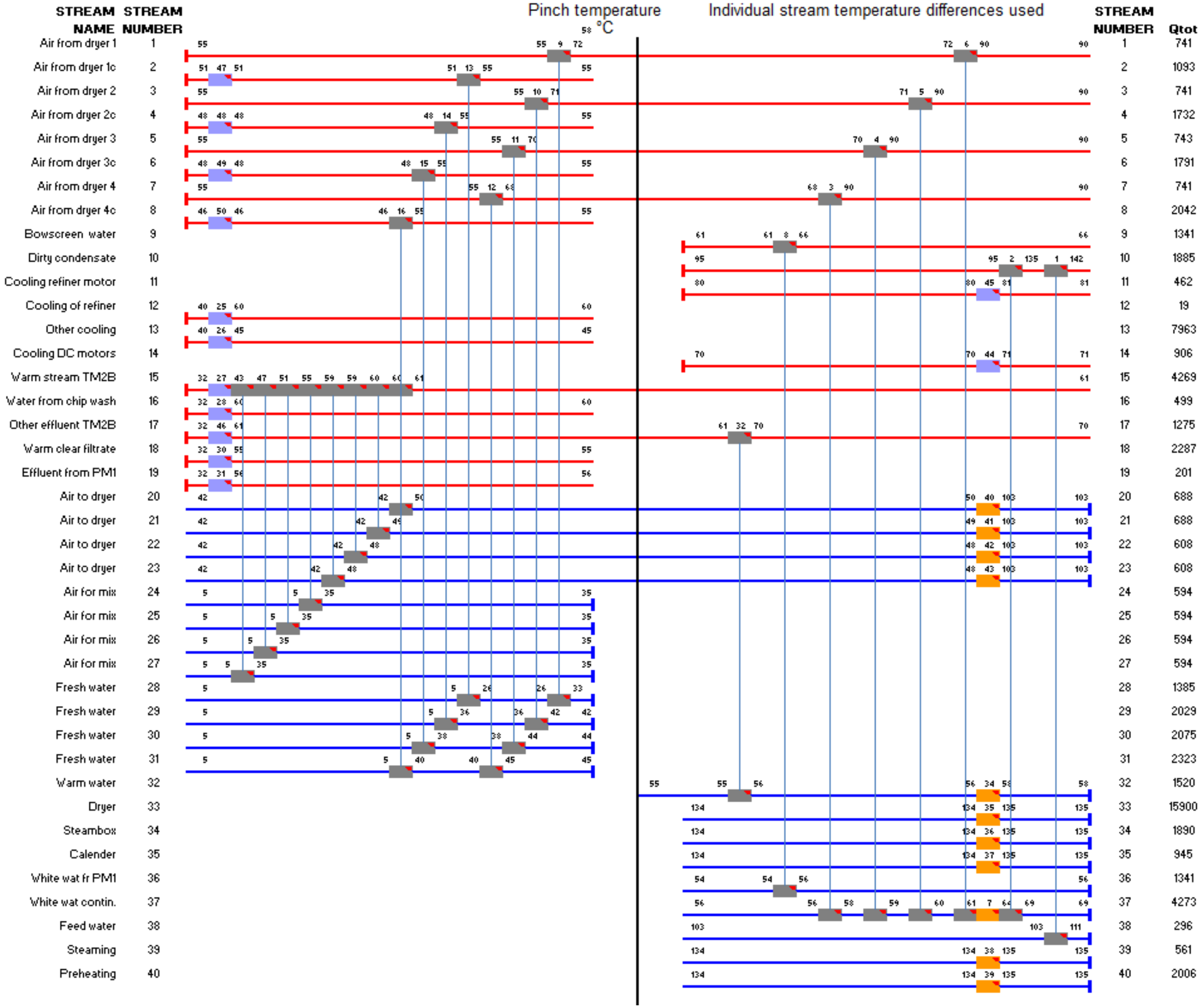

Figure 22 Network representation. Retrofit 3 – deluxe

5.4 Summary the retrofits based on changes in the heat exchanger network

As previously stated the three retrofits presented in Section 5.1-5.3 vary in complexity and energy-savings. The savings achieved with the different retrofits of the existing heat exchanger network are illustrated in Figure 23 as a percentage of the potential of savings of a MER network. It can be seen that high steam savings can be achieved in Retrofit 2 – medium and Retrofit 3 – deluxe where the paper machine heat recovery system is modified.

As mentioned in the previous sections, the retrofits vary in degree of complexity so the savings achieved in the third retrofit are naturally higher than in the second and the first retrofits. Since the cost of the retrofit increases with increasing complexity, a guess would be that the third retrofit is more expensive than the first one and the second one. It is unfortunately impossible to define which retrofit that is the most profitable unless and economic study is carried out.

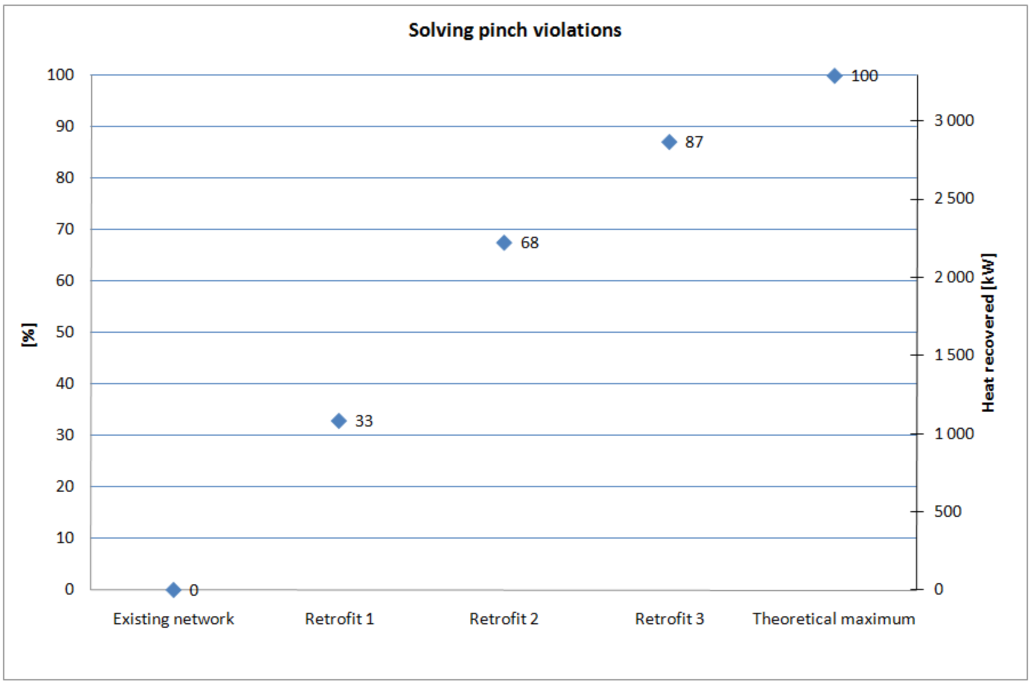

Figure 23 Hot utility savings in the different retrofits

5.5 Retrofit 4 - Preheating opportunities

In addition to retrofitting the existing heat exchanger network, opportunities for improving the system by preheating some streams with waste heat available was identified, hereafter called preheating opportunities. Two main preheating opportunities were identified: preheating the dilution water to the refiners' discs and preheating the impregnation water.

In the following section, a discussion about the way the preheating opportunities are identified is presented. The real steam savings achieved when implementing the preheating opportunities in the existing network, as well as in the Retrofits 1-3 is discussed afterwards.

Identification of preheating opportunities

With the help of the GCC of the system it was possible to identify heat available at temperature levels that can be used for preheating streams (see Figure 24). According to the GCC, it is possible to implement the preheating opportunities even in a MER network, i.e. a network in which the internal heat recovery is maximized. The existing network and in Retrofits 1-3 have more pinch violations and consequently more heat available in hot streams that are not used to recover heat internally, as a consequence it is theoretically possible to implement the preheating opportunities in combination with all these heat exchanger network configurations.

In practice, it is convenient that the preheating is done by a single stream rather than several hot streams. Under these circumstances, there might not be possible to implement the preheating opportunities if there is not any suitable stream that can satisfy this heating demand by itself. For the preheating opportunities presented in the following sections the other effluent from TM2B (stream 17) was considered to be the best stream to be used for preheating as it has 1275 kW of heat available at a higher temperature than 32 °C.

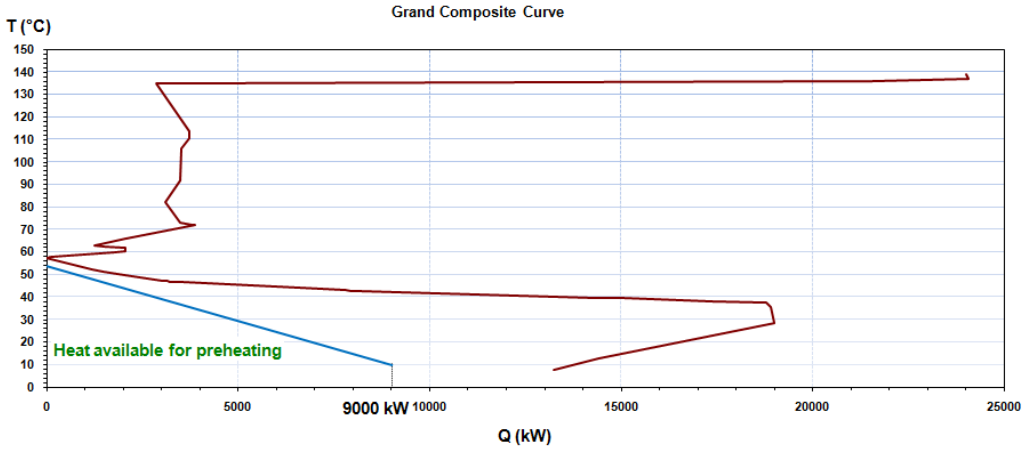

Figure 24 Identification of preheating opportunities

Preheating of dilution water to the refiners

Under operation of the high consistency refiners[27] steam is produced from the dilution water (that is needed to cool the discs). When dilution water is added, it is immediately heated to high temperatures and evaporated into dirty steam. The dirty steam is then transformed to clean steam in the reboiler.

When dilution water enters the refiners, friction heat brings the boiling temperature and then evaporates it. If dilution water is fed at a low temperature, more heat is needed to bring it to its boiling temperature than if the dilution water is hot.

The limitation when preheating dilution water is to identify the temperature up to which water can be heated without affecting the operation of the refiner negatively. This dilemma was discussed with the Research Manager of the Paper and Fibre Research Institute, Lars Johansson who confirmed that it is possible to heat the dilution water up to the boiling point and even pressurized to temperatures higher than 100 °C without causing any malfunction in the refiner.

Considering a MER network and assuming that as many streams as needed can provide the heat needed for preheating, it is possible to generate 0.5 MW more of clean steam, by preheating the dilution water from 44 °C to 55 °C reducing thus the need for external hot utility. These calculations can be found in Appendix 7.

In the existing system and in Retrofits 1-3 the possibility of preheating the dilution water with an effluent stream (stream 17) was investigated. The total clean steam savings achieved are presented in Table 21.

Table 21 Clean steam savings, preheating dilution water

	Heating demand [MW]	**Dirty steam [MW]**	**Clean steam [MW]**
Existing network	0.53	0.53	0.46
Retrofit 1- 3	0.24	0.24	0.21

Preheating impregnation water

In the pulp plant the wood chips are sent to an impregnation tower before they enter the preheater. In the impregnation tower the wood chips are impregnated with water, called impregnation water. After the impregnation the chips have a more uniform moisture profile which eases the refining.

The chips and the impregnation water enter the impregnation tower at 70 °C and 10 °C respectively. After the impregnation the chips have a temperature of 54 °C. The chips are then preheated by dirty steam to a temperature of 120 °C.

If the impregnation water is preheated from 10 °C to a higher temperature the chips would enter the preheater at a higher temperature and consequently the preheating steam demand would decrease.

---

[27] For a description of the steam recovery system please refer to section 3.3.1.

Research has shown that preheating of impregnation water does not have a negative effect on the impregnation process and theoretically the temperature can be increased up to the boiling point. Furthermore, a higher temperature of the impregnation water gives a higher impregnation rate. However, in practice the increased impregnation rate is not noticeable. The reason for this is that the higher temperature has some negative effects on the impregnation as by thermal expansion of the gaseous mixture in the chip voids [15].

Considering a MER network and assuming that as many streams as needed can provide the heat needed for preheating, it is possible to reduce the dirty steam demand by 0.43 MW, 21 %. If the capacity of the reboiler was larger, this dirty steam could be transformed into 0.38 MW of clean steam. By using hot steams as heat sources the system's cooling demand can be reduced with 0.75 MW. These calculations can be found in Appendix 8.

In the existing system and in Retrofits 1-3 the possibility of preheating the impregnation water with an effluent stream (stream 17) was investigated. The total clean steam savings achieved are the same for all the cases. This is presented in Table 22.

Table 22 Clean steam savings, preheating impregnation water

	Heating demand [MW]	**Dirty steam [MW]**	**Clean steam [MW]**
Existing network, Retrofits 1-3	0.75	0.43	0.38

Limitations of steam recovery

The dirty steam produced in the refiners is send to the reboiler, the steaming and preheating and the surplus steam is send to the scrubber. The reason for sending dirty steam to the scrubber instead of to the reboiler is the limited capacity in the reboiler.

Capacity tests of the reboiler gave results of 16.6 MW, 16.8 MW and 17.3 MW of clean steam, depending on the electricity demand for different pulp productions. In the study presented in this thesis a reboiler capacity of 16.8 MW is used. Currently 4.3 MW of dirty steam is sent to the scrubber. If a reboiler with higher capacity was installed (with the same efficiency as the old one) 3.7 MW of additional clean steam could be produced. Additionally, the preheating opportunities could be implemented. The summary of the clean steam savings for preheating opportunities is presented in Table 23. More information about the reboiler is found in Appendix 9.

Table 23 Summary results, Retrofit 4

Clean steam savings [MW]

	Dilution water to the refiners	**Impregnation water**	**Dirty steam to the scrubber**	**TOTAL**
Existing network	0.46	0.38	3.76	4.60
Retrofits 1-3	0.21	0.38	3.76	4.34

A summary of the preheating opportunities and the use of steam send to the scrubber together with a reboiler with a higher capacity are presented more in detail in Appendix 10.

5.6 Retrofit 5 – Heat pump

A heat pump is a device that takes heat from a stream at a low temperature and delivers heat at a higher temperature. It is therefore possible to achieve steam savings if a heat pump is installed across the pinch i.e. by removing heat from below the pinch where the system has an excess of heat and delivering heat above the pinch where the system has deficit of heat.

Identification of heat pump opportunities

Similarly to the preheating opportunities, the possibility to integrate a heat pump in a MER network can be studied with the GCC. In practice however, the potential for savings is different, as the heat exchanger network does not recover as much heat internally and as it may be convenient to select one single stream as a heat source rather than several hot streams.

In Figure 25, heat available at 42 °C is lifted to 69 °C where the system has a heat deficit. For this relatively small temperature lift a closed compression cycle heat pump is ideal and it would lead to about 2.8 MW of steam savings with an electricity demand of 0.6 MW.

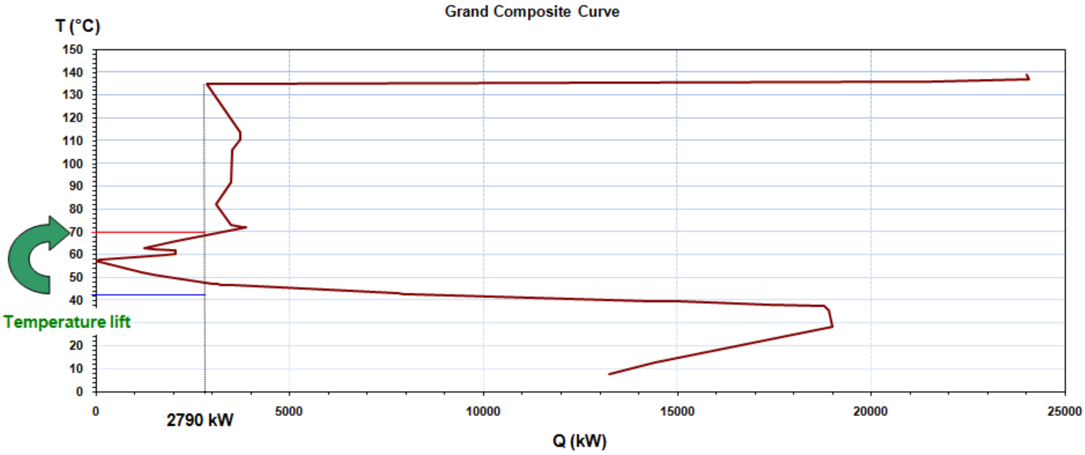

Figure 25 Integration of a heat pump, closed compression cycle.

Of the streams that have heat available below the pinch, the warm stream leaving TM2B (stream 15) was considered to be an interesting option for the heat source in the heat pump. This is due to the fact that the heat pump demand of 2.8 MW can be covered by this stream alone due to its high heat content. The warm stream leaving TM2B is currently sent to the effluent treatment plant and demands 4.3 MW of cold utility. Similarly, the stream of white water (stream 37) was considered to be a good heat sink as it currently consumes 4.3 MW of steam. Consequently, the heat exchanger design for this kind of heat pump is simpler than if more than one stream were needed as a heat source or sink. Additionally, the heat transfer properties of these two liquid streams are better than gaseous streams such as air from the dryer (streams 1-8), which makes the heat exchange area required smaller.

For a MER network, only 2.8 MW are needed above the pinch so it is not necessary to use all the flow of the warm stream leaving TM2B. The heat demand of the heat pump can be covered by 80% of this stream and the rest of the heat can be used elsewhere. The heat delivered is sufficient to heat 65% of the white water stream. A scheme of the heat pump proposed is illustrated in Figure 26. The heat pump calculations and the assumptions made are presented in Appendix 11.

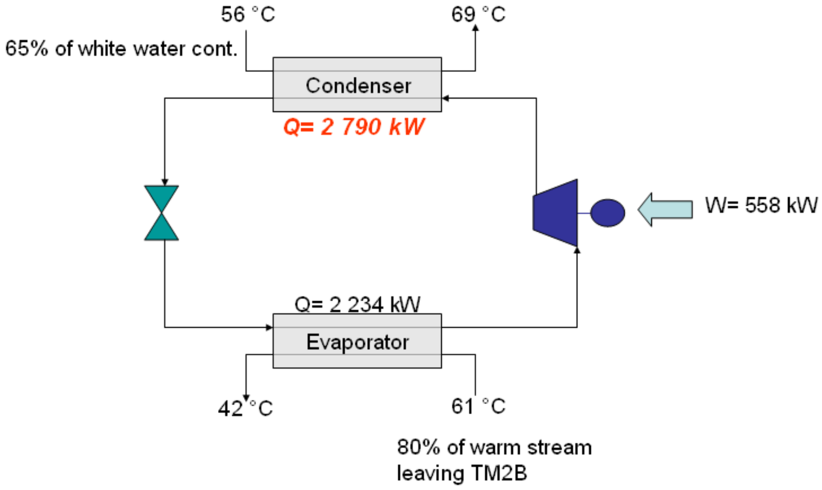

Figure 26 Heat pump representation, integration in a MER network

In the arrangement shown in Figure 26 it is assumed that 9.3 kg/s of n-butane are used as a refrigerant. The evaporator operates at 3 bar and n-butane evaporates at 32 °C. The condenser operates at 9 bar and n-butane condenses at 79 °C. The heat pump demands 0.6 MW of compressor work. The heat pump has a coefficient of performance (COP)[28] of 5.

Integration of a heat pump

In the existing network as well as in Retrofit 1, the warm stream leaving TM2B (stream 15) has more heat available and the heat pump can deliver 3.5 MW of heat above the pinch. In Retrofits 2-3 the warm stream leaving TM2B has much less heat available and the heat pump can deliver only 1.1 MW and 0.2 MW respectively. The total heat recovered for each heat exchanger configuration is summarized in Table 24.

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[28] The coefficient of performance is an indicator of how much heat is delivered in the condenser respect to the work added in the compressor.

Table 24 Summary results, Retrofit 5

	Q_{evap} [MW]	**W_{comp} [MW]**	**Q_{cond} [MW]**
Existing network and Retrofit 1	2.80	0.70	3.50
Retrofit 2	0.87	0.22	1.09
Retrofit 3	0.13	0.03	0.16

5.7 Summary and possible combinations of the presented retrofit solutions

In the previous sections, alternative solutions for retrofit of the studied system have been presented. In section 5.1-5.3 the possibilities for improving the heat exchanger network were presented. In section 5.5 the possibility of preheating certain streams in order to produce more steam was introduced and finally, in section 5.6 the integration of a heat pump was discussed. These different retrofit solutions can be implemented independently or in combination with each other. A discussion of the possible combinations is presented in Appendix 12. A summary of the possible heat recover for the different retrofits, and combinations of retrofits is found in Table 25.

Table 25 Steam saving potentials for combinations of the presented retrofit solutions

Total heat recovered [MW]

Heat exchanger network configuration	**Retrofitting HX-network alone**	**Retrofit 4 - Preheating opportunities**	**Retrofit 5 - Heat pump**	**Retrofit 4+ Retrofit 5**
Existing network	0.0	4.6	3.5	8.1
Retrofit 1	1.1	5.4	4.6	8.9
Retrofit 2	2.2	6.6	3.3	7.6
Retrofit 3	2.9	7.2	3.0	7.4

The maximum steam savings are achieved when Retrofit 1 – Light is combined with Retrofit 4 and Retrofit 5 (preheating opportunities and heat pump). In this way 8.9 MW of steam can be saved. The second best alternative is to combine the existing network with Retrofit 4 and Retrofit 5 (preheating opportunities and heat pump), where 8.1 MW of steam are saved. As mentioned in section 5.5, implementation of Retrofit 4 requires investing in a reboiler with a larger capacity.

6 Future scenarios

In the following sections two future scenarios are discussed concerning the impacts on the energy situation of the mill. In the first scenario recycled paper and filler are introduced and in the second scenario recycled paper and filler are introduced together with more energy efficient refining.

6.1 Scenario with recycled paper and filler

In a future scenario 20 % recycled paper (DIP) and 10 % filler are introduced. This reduces the costs as the production of energy intensive TMP production can be reduced by 30 %. However, less electricity used for the TMP production also means a reduction of steam production since some of the electricity used in the refiners is recovered as steam as described in section 3.3.1. Therefore it is interesting to investigate if a retrofit that decreases the process steam demand of the studied system, as described in preceding sections, would be enough to cover this steam utility reduction.

The current clean steam production in the TM2B plant is 16.8 MW and the surplus of dirty steam, not utilized in the reboiler, is 6.8 MW. After introduction of 20 % DIP and 10 % filler the clean steam production in TM2B will be 14.4 MW and the dirty steam, not utilized in the reboiler, will be 4.8 MW.

Added to the reduced steam production due to the lower refiner load there is also a reduction in falling bark due to the reduction of logs used for TMP production. For every kg of timber arriving to the plant about 8.9 % is bark. The bark is recovered from the debarking process and used as fuel in the boiler house, ending up as steam that is used as hot utility. The bark from every BDkg of TMP produces 0.74 kg of steam, 1.6 MW. The clean steam from the bark before the introduction of DIP and filler is 8.8 MW. If no additional bark is bought to replace the reduced bark amount the reduction of steam from the boiler house will be 2.6 MW, resulting in 6.1 MW of clean steam.

However, in this scenario the system also uses DIP. In the production of DIP, DIP sludge is generated and used as a fuel in the boilers. The 20 % recycled paper will give an addition of steam production of 0.2 MW by the DIP sludge. Figure 27 shows a schematic picture of the existing system and the scenario with introduced DIP and filler.

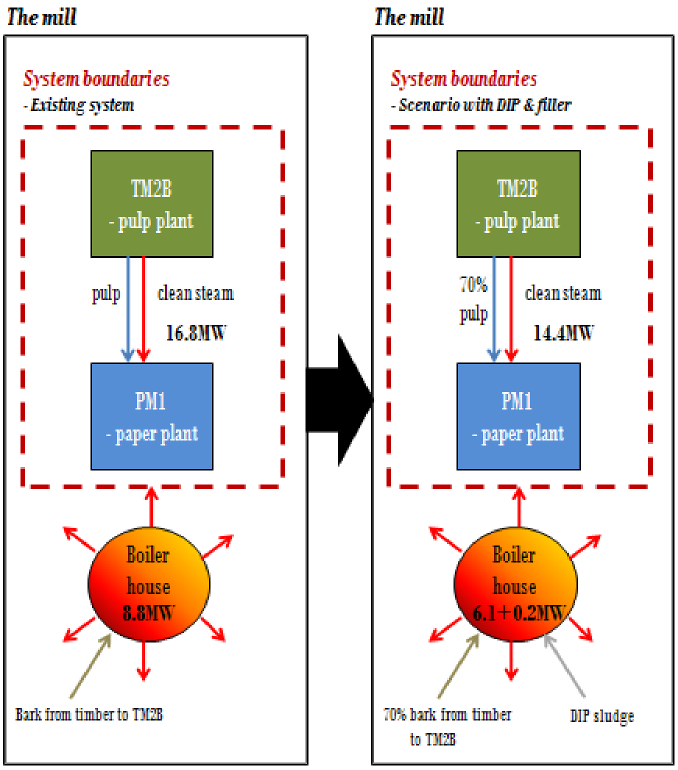

Figure 27 The existing system and the scenario with DIP and filler introduced.

The total clean steam production in the boilers and in the pulp plant, TM2B, after the introduction of DIP and filler will be 20.7 MW compared to the total clean steam production of 25.6 MW before the change. Figure 28 shows the reduction of the steam production after the introduction of DIP and filler and Figure 29 shows the reduction in production of dirty steam after the introduction of DIP and filler. Dirty steam production refers to the production of dirty steam which is used by dirty steam consumers (steaming, preheating and scrubber), the dirty steam to the reboiler is not included in this amount as it is converted into clean steam. The reduction of clean steam production and dirty steam production can also be seen in Table 26.

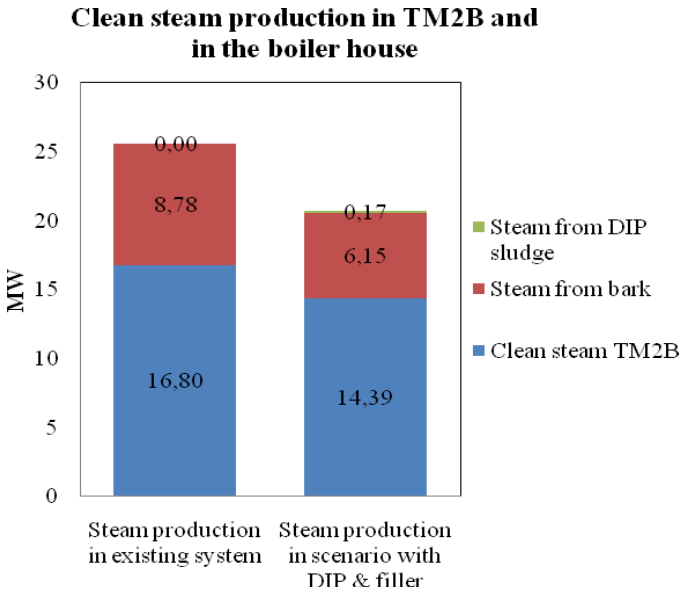

Figure 28 The clean steam production in TM2B and in the boiler house in the existing system and in the scenario with DIP and filler

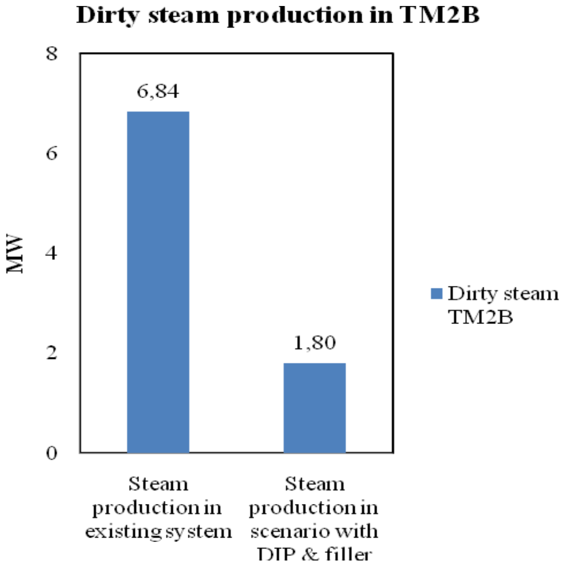

Figure 29 The dirty steam production in TM2B in the existing system and in the scenario with DIP and filler

Table 26 The reduction of dirty steam production and clean steam production between the existing system and the scenario with DIP and filler

	Existing system	***Scenario with DIP and filler introduced***	***Change***
Dirty steam production [MW]	6.8	1.8	-5
Clean steam production [MW]	(16.8)[29] 25.6[30]	(14.4)[29] 20.72[31]	(-2.4) -4.88

As can be seen from the diagrams the production of clean steam and the production of dirty steam are both reduced. However, as the production of TMP is reduced the TM2B plant will not need as much steam for its processes. The steaming process and preheating process, which use dirty steam, reduces its steam demand by 0.8 MW from 2.6 MW to 1.8 MW. In this scenario the dirty steam production is adjust to provide dirty steam only to the steaming and the preheating process. The remaining dirty steam is converted into clean steam in the reboiler as the reboiler after the reduced TMP production is running below its maximum capacity, 16.8 MW. Before the introduction of DIP and filler the usage of clean steam is 26.1 MW and after introduction of DIP and filler it is 24.7 MW. The reduction is due to the reduced clean demand in TM2B of 1.3 MW, stream 37 that dilute the pulp after a screw press has a reduced steam demand. The changes in dirty steam demand and clean steam demand are presented in Table 27.

Table 27 The change in dirty steam and clean steam demand between the existing system and the scenario with DIP and filler introduced

	Existing system	***Scenario with DIP and filler introduced***	***Change***
Dirty steam demand			
Steaming [MW]	0.6	0.4	-0.2
Preheating [MW]	2.0	1.4	-0.6
Total [MW]	**2.6**	**1.8**	**-0.8**
Clean steam demand			
Stream 37 [MW]	4.3	3.0	-1.3
Total [MW]	**4.3**	**3.0**	**-1.3**

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[29] The clean steam production only in TM2B, within the system boundaries

[30] Clean steam produced in TM2B and clean steam produced in the boiler house (bark as fuel), therefore the latter is not inside the system boundaries but must be included in the analysis as the scenario not only cause changes within the system but also outside.

[31] Clean steam produced in TM2B and clean steam produced in the boiler house (bark and DIP sludge as fuel), therefore the latter is not inside the system boundaries but must be included in the analysis as the scenario not only cause changes within the system but also outside.

The retrofits based on a rebuild of the heat exchanger network alone, presented in section 5.1-5.3, will give a reduced clean steam demand but this process steam reduction will not be enough to cover the reduction of clean steam production, this can be seen in the first column under *Retrofitting heat exchanger network alone* in Table 28. The comparison is made by subtracting the reduction of clean steam production from the reduction of clean steam demand from the retrofits, positive result means that the reduction of clean steam production in covered by the reduction of clean steam demand from the retrofits and negative result means the opposite.

However, the preheating opportunities of the impregnation water and the dilution water for the refiners (Retrofit 4) can give further steam. This increase can be accomplished without a new reboiler as the reboiler in the scenario is running below its maximum capacity. With the preheating opportunities the steam demand of the system is reduced by 0.8 MW. Retrofit 5, the heat pump configuration, can also give further steam savings. With an installed heat pump the steam demand of the system is decreased by 3.5 MW. A combination between Retrofit 4 and Retrofit 5 the steam demand can be decreased by as much as 4.3 MW.

The combination of Retrofit 4 and Retrofit 5 in the existing system is not enough to cover the reduced clean steam production, retrofits solving pinch violations would also be needed. Combinations between retrofits solving pinch violations and Retrofit 4 and or Retrofit 5 or a combination of them both, can give even more clean steam demand reduction of the system. The only combination which can cover the steam deficit from the scenario is Retrofit 1 with Retrofit 4 and Retrofit 5. The calculations for the scenario with DIP and filler introduced are presented in Appendix 13.

Table 28 Clean steam surplus or deficit in scenario with DIP and filler introduced

Heat exchanger network configuration	**Retrofitting heat exchanger network alone**	**Retrofit 4 (preheating opportunities)**	**Retrofit 5 (heat pump)**	**Retrofit 4+ Retrofit 5**
Surplus/deficit steam in existing system [MW]	**-4.9**	**-4.0**	**-1.4**	**-0.5**
Surplus/deficit steam in Retrofit 1 [MW]	**-3.8**	**-3.2**	**-0.3**	**0.3**
Surplus/deficit steam in Retrofit 2 [MW]	**-2.7**	**-2.1**	**-1.6**	**-1.0**
Surplus/deficit steam in Retrofit 3 [MW]	**-2.0**	**-1.4**	**-1.9**	**-1.3**

6.2 Scenario with recycled paper and filler together with more energy efficient refining

In a future scenario the studied system utilize more energy efficient refining. This scenario is based on the scenario with recycled paper (DIP) and filler since the mill intends to implement it within one year.

The most energy intensive part in the pulp and paper mill is the chip refining. After the recent rebuild the pulp plant consist of both high and low consistency refiners, something which reduced the electricity demand for the refining process. However, there is a high interest in reducing the electricity use in the pulp plant even further in the future. Examples of measures which can reduce the electricity use in the pulp plant are to have a mechanical pre-treatment of the chips before the refiners or use higher refining intensity which can mean a change from the existing refiners into double disc refiners or increasing the rotational speed on the existing ones [3]. The first measure would lead to an electricity use reduction by 5 % and the latter by 15 %.[32]

More energy efficient refining will lead to less steam production as less electricity input means less heat output from the refiner, as described in previous section. This will lead to a higher demand of external hot utility production, e.g. from a boiler burned with bark or oil.

The scenario with more energy efficient refining is divided into two measures, investigated separately. The first measure is to introduce a mechanical pre-treatment process of the chips which reduces the electricity usage by 5 %. The second measure is to change the refining into higher refining intensity. In the second measure the mechanical pre-treatment measure is also included and therefore the total reduction of the electricity use is 20 %. Figure 30 shows a schematic picture of the existing system and the scenario with introduced DIP and filler and more energy efficient refining (the figures related to the measure mechanical pre-treatment of chips and mechanical pre-treatment of chips together with higher refining intensity are separated with a slash).

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[32] Lars Johansson (Paper and Fibre Research Institute) emails and discussions during March and April 2009.

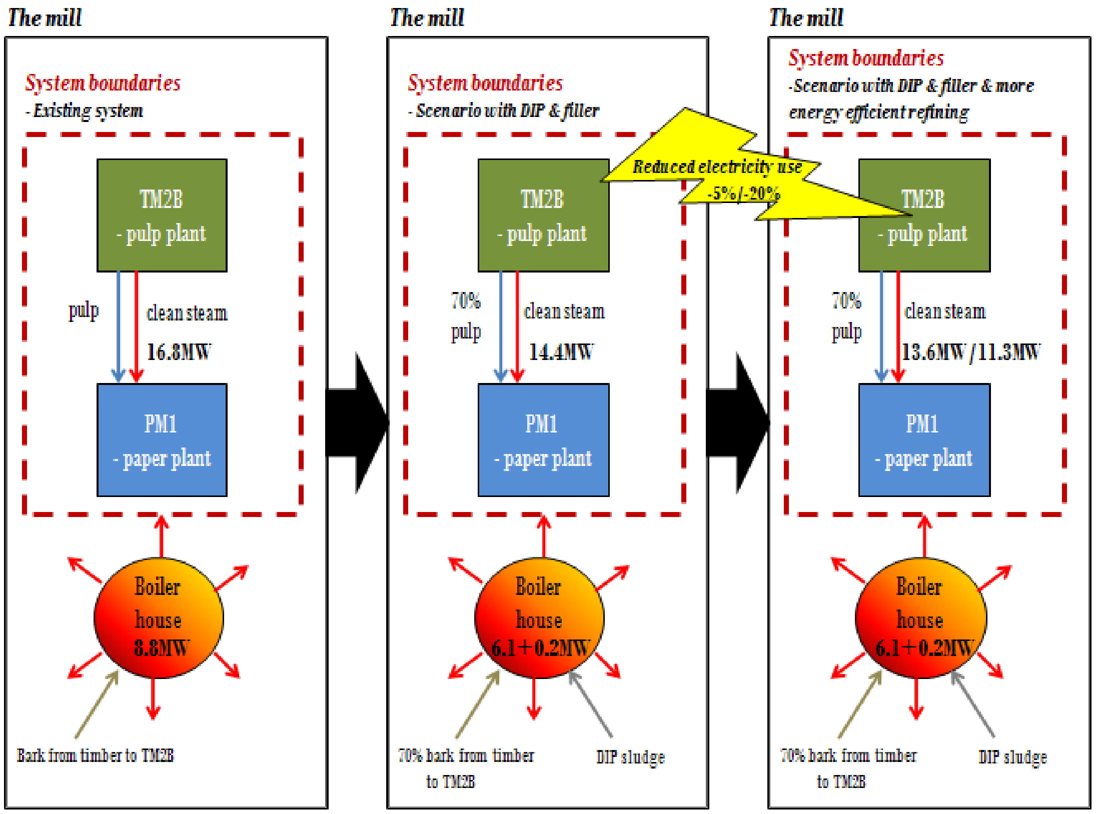

Figure 30 The existing system and the scenario with DIP and filler introduced and more energy efficient refining.

Higher intensity of the refiners can be reached by increasing the rotational speed of the refiners but if this is not enough only an investment in new double disc refiners would give the electricity use reduction of 20 %. It is less costly to make changes before the refiners than to buy new refiners which makes the mechanical pre-treatment more favourable for the TM2B plant as the studied system recently has been rebuilt, making more investments seem less likely in the near future. However, since the mechanical pre-treatment reduces the electricity consumption with 5 % compared to 20 % if combination with higher refining intensity it might be considered too small a gain for an investment. Figure 31 shows how the steam production is affected by either mechanical pre-treatment or mechanical pre-treatment in combination with higher refining intensity compared to the existing system.

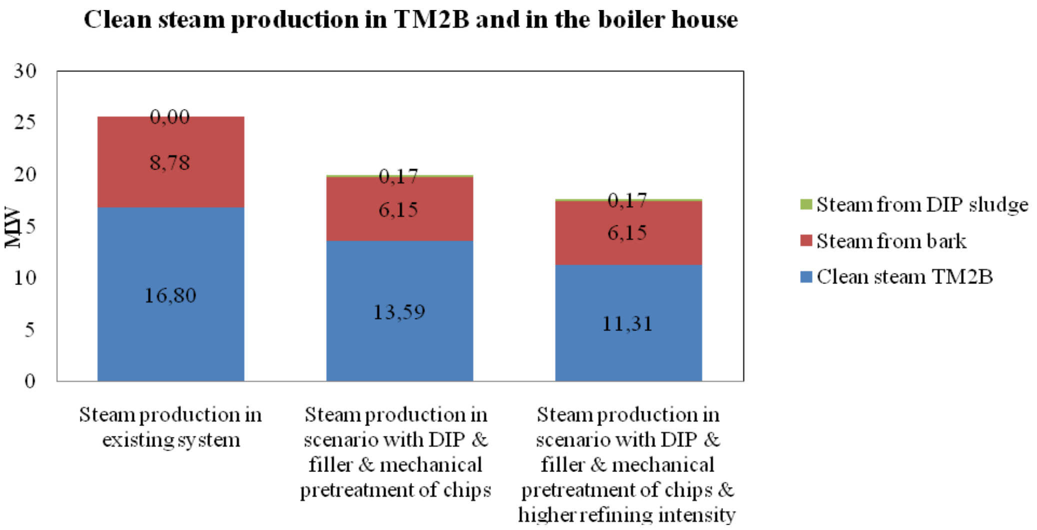

Figure 31 The clean steam production before and after the introduction of DIP and filler and more energy efficient refining.

If mechanical pre-treatment of the chips is introduced, the steam production is reduced to 19.9 MW and if mechanical pre-treatment is introduced together with higher refining intensity, the steam production is reduced to 17.6 MW. The amount of dirty steam production (for steaming, preheating and scrubber) is also reduced as can be seen in Figure 32. The reduction of clean steam production and dirty steam production can also be seen in Table 29.

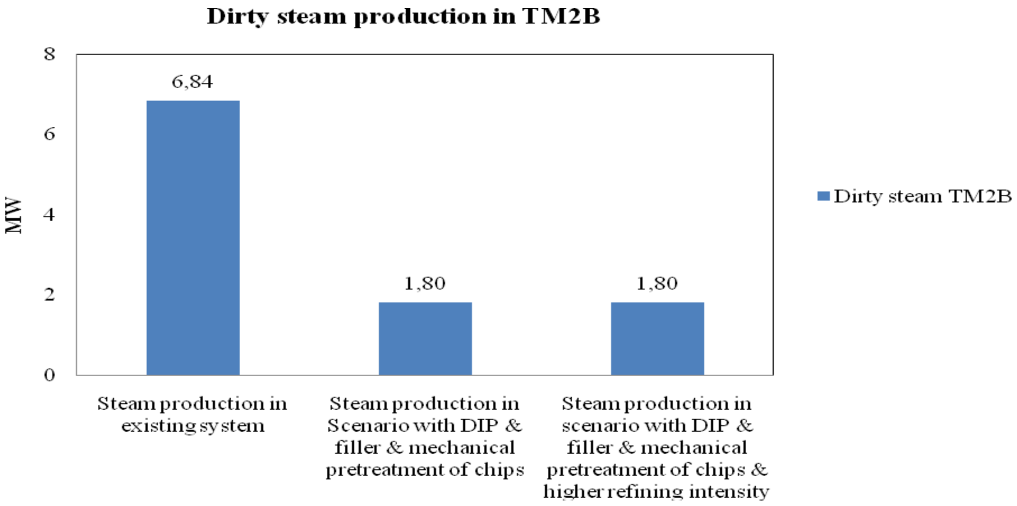

Figure 32 The dirty steam production before and after the introduction of DIP and filler and more energy efficient refining.

As in the scenario with DIP and filler the dirty steam production is adjust to provide dirty steam only to the steaming and the preheating process. The remaining dirty steam is converted into clean steam in the reboiler. The steamer and the preheater have the same dirty steam demand as in the scenario with DIP and filler, 1.8 MW, as seen in Table 4 in section 3.2.

Table 29 The change in dirty steam and clean steam demand between the existing system and the scenario with DIP and filler introduced and mechanical pre-treatment of chips with or without higher reefing intensity

	Existing system	***Scenario with DIP & filler introduced & mechanical pre-treatment of chips***	***Change***	***Scenario with DIP & filler introduced & mechanical pre-treatment of the chips & higher refining intensity***	***Change***
Dirty steam production [MW]	6.8	1.8	-5	1.8	-5
Clean steam production [MW]	(16.8) 25.6	(13.6)[29] 19.9[31]	(-3.5) -5.7	(11.3)[29] 17.6[31]	(-5.5) -8

The reduction of clean steam production after the mechanical pre-treatment of the chips and the mechanical pre-treatment of the chips together with higher refining intensity compared to the reduction of clean steam demand, both for the existing system and in the three different retrofits solving pinch violations in the heat exchanger network, is presented in Table 30. In the table the measures of mechanical pre-treatment of chips and mechanical pre-treatment of chips together with higher refining intensity are presented next to each other separated with a line. The comparison is made by subtracting the reduction of clean steam production from the reduction of clean steam demand from the retrofits, positive result means that the reduction of clean steam production in covered by the reduction of clean steam demand from the retrofits and negative result means the opposite.

The retrofits solving only pinch violations in the heat exchanger network will give a reduced steam demand but this process steam reduction will not be enough to cover the reduction of clean steam production. However, the preheating opportunities of the impregnation water and the dilution water for the refiners (Retrofit 4) can give further steam. This increase can be accomplished without a new reboiler as the reboiler in the scenario is running below its maximum capacity. With the preheating opportunities the steam demand of the system is reduced by 0.8 MW. Retrofit 5, the heat pump configuration, can also give further steam savings. With an installed heat pump the steam demand of the system is decreased by 3.5 MW. A combination between Retrofit 4 and Retrofit 5 can decreased the steam demand by as much as 4.3 MW.

The combination of Retrofit 4 and Retrofit 5 in the existing system is not enough to cover the reduced clean steam production, retrofits solving pinch violations in the heat exchanger network would also be needed. The only combination which almost can cover the reduced steam production in the scenario with mechanical pre-treatment of chips is Retrofit 1 with Retrofit 4 and Retrofit 5. No combination of retrofits will cover the steam production deficit of the scenario with mechanical pre-treatment of chips and higher refining intensity. The calculations for the scenario with DIP and filler introduced and more energy efficient refining are presented in Appendix 13.

Table 30 Clean steam surplus or deficit in scenario with DIP and filler introduced and mechanical pre-treatment of the chips with or without higher refining intensity

Heat exchanger network configuration	**Retrofitting heat exchanger network alone**	**Retrofit 4 (preheating opportunities)**	**Retrofit 5 (heat pump)**	**Retrofit 4+ Retrofit 5**
Surplus/deficit steam in existing system [MW]	-5.7| -8.0	- 4.8| -7.1	- 2.2| -4.5	- 1.3|- 3.6
Surplus/deficit steam in Retrofit 1 [MW]	- 4.6| -6.9	- 4.0| -6.3	- 1.1| -3.4	- 0.5|-2.8
Surplus/deficit steam in Retrofit 2 [MW]	- 3.5| -5.7	-2.9| -5.1	- 2.4| -4.6	- 1.8 -4.1
Surplus/deficit steam in Retrofit 3 [MW]	- 2.8| -5.1	- 2.2| -4.5	- 2.7| -4.9	- 2.1| -4.3

7 Discussion

In the previous sections the most important results of this thesis were presented. Firstly, it was shown that the steam consumption of the studied system is larger than for the MER case. An analysis of the current network revealed that the major sources of pinch violations in the existing heat exchanger network are:

1. Paper machine heat recovery system: The integrated heat recovery system above PM1 is the biggest source of pinch violations. It accounts alone for 2.1 MW of heat transferred through the pinch, corresponding to 45% of all the pinch violations. This means that the air from the dryer (streams 1, 3, 5, 7) is at a high temperature and is currently heat exchanged with low temperature streams. A more efficient way to recover this heat would be to use it to heat streams that need to be heated to higher temperatures.
2. Cooling of refiners' motors and DC motors (streams 7, 8): The way this cooling is achieved is the second biggest source of pinch violations. It accounts for 29% of all the pinch violations. In this thesis, this cooling was considered to be unchangeable but it was represented in the network with the purpose to point out that the cooling is achieved inefficiently. Nevertheless, in Skogn, the cooling is achieved cheaply and there is no big drive to modify it.
3. District heating system: The way the dirty condensate (stream 10) is used to heat district heating water which is used to heat the air for mixing (streams 24-27) and the air to dryer (streams 20-23) the third largest pinch violation. The district heating system accounts for 19% of all the pinch violations in the system. While the district heating system may be a convenient way to deliver heat in different places of the mill, the heat exchange is often inefficient. Alternatives ways to satisfy the heating demands would be interesting to explore.

The rest of the pinch violations in the system from all the other places in the mill account only for 6% of the total pinch violations. This may be considered to have a minimal influence in the total potential for heat savings.

The proposed retrofits of the existing heat exchanger network vary in their complexity level. In the first retrofit some district heating system violations were solved but no modifications to the paper machine heat recovery system are made. The heat recovered is 33 % of the savings achieved with a MER network. In the second and third retrofits, the heat recovery system was modified and this allowed reaching correspondingly 68 % and 87 % of the maximum potential. It is clear that the possibility to achieve energy savings is limited if the paper machine heat recovery system is not modified.

The preheating opportunities of the dilution water for the refiners and the impregnation water was investigated to see if there was a possibility to obtain more steam production in the pulp plant. Unfortunately, the capacity of the present steam recovery system is too low, hence at present the surplus of dirty steam from the preheating opportunities cannot be recovered as clean steam. It was found that a substantial amount of dirty steam is currently sent to the scrubber but could be used if the steam recovery system had, as in the case of the preheating opportunities, a higher capacity. The replacement of the existing reboiler with a reboiler with higher capacity has been discussed for some years at the mill. The results from this analysis advocate this investment. However, if the system boundaries would have been larger maybe the dirty steam could be converted into clean steam in another reboiler, e.g. the reboilers in TM1 and TM2A, if these are running below their maximum capacity.

Integration of a heat pump seemed to be a very promising option. A heat pump could raise heat that is currently not used (below the pinch) to a temperature level that is useful in the process (above the pinch). A heat pump could recover as much as 3.5 MW of heat, which is larger than the savings achieved by Retrofits 1-3. As fewer changes are needed to integrate a heat pump than to rebuild the heat exchanger network as in the proposed retrofits, it is probable that the investment cost would be lower. This should however be confirmed by a proper economical study.

It was possible to combine the different retrofits with each other to achieve further savings. The largest savings were obtained by combining the preheating opportunities and the heat pump simultaneously with Retrofit 1, the existing network, Retrofit 2 and Retrofit 3 in that order. It is interesting to notice that the most modified heat exchanger networks achieve worse steam savings than the simpler ones since the potential steam savings from the other suggested retrofits, preheating and heat pump then cannot be fully utilized. This may point towards modifying the existing network only lightly.

In a future scenario, when 20% recycled paper and 10 % filler are introduced, both the clean steam production and the dirty steam production are decreased. The reduction of clean steam is compared to the reduced clean steam demand which can be achieved through different retrofits or by combinations of retrofits. The combination of Retrofit 1 with preheating opportunities (Retrofit 4) and a heat pump (Retrofit 5) is the only combination which can meet up to the reduced steam production. Retrofit 4 include only the preheating opportunities and no new reboiler is needed in both scenarios as the reboiler is running below its maximum capacity. When the reduction of clean steam production is not met up by the remaining combinations this implies an increased fuel demand. However, as less pulp would be produced, the plant will have a reduced electricity consumption which could be more favourable despite of the increase of demand for steam produced in the boiler house.

In the second scenario not only 20 % recycled paper and 10 % filler is introduced but also the refining process is more energy efficient. The steam production in the second scenario is even further reduced. The reduction of clean steam is compared to the reduced clean steam demand which can be achieved through different retrofits or by combinations of retrofits. No combination of retrofits can cover the steam production deficit of the scenario with mechanical pre-treatment of chips with and without higher refining intensity. However, as the electricity consumption is reduced it could be more favourable despite the reduction of clean steam production. When the clean steam production in TM2B is reduced, as in both scenarios, additional steam must be produced in the boiler house. The fuel options are bark, oil or electricity. Oil and electricity is only used 2 % and 1 % respectively of the total fuel usage. This indicates that most likely more biomass would be purchased to cover the increased steam demand.

As one can see in Figure 27 in section 6.1 and Figure 30 in section 6.2, the analysis of the two scenarios also include the effects on the whole mill even though it is outside the system boundaries in this thesis. Still, if changes in the studied system affect the system outside these changes have to be included in the analysis in order to keep the outside system constant e.g. the steam from the boiler house is part of the auxiliary system and when less bark is burnt less steam will be produced.

The main problem of only studying one part of a mill is that the possibilities of improving the process integration are restricted by the system boundaries. A study of the whole mill would achieve more steam savings compared to several studies of each part of the mill.

7.1 Comparison of the results with a similar study of a TMP model mill

In this section the results from this thesis will be compared to a similar study of a model mill. The studied system in this thesis is a part of a real mill, Skogn mill, and will in this section be called “a real mill” for simplicity.

As mentioned in the background Axelsson [6] is one study that has been of interest for the work presented in this thesis. In the study by Axelsson a model of a TMP mill with the best available techniques developed by Anders Lundström (STFI-Packforsk) and Martin Åberg (ÅF) was analysed. The model mill included a pulp line, a paper machine and an auxiliary hot and cold utility system.

The pulp production was 272 000 ADton pulp per year. The paper production was 456 000 ton per year. The refiner process in the mill had a power demand of 100 MW and 86 MW of this was recovered as steam. Before any retrofit the mill already had a steam surplus of 21.5 MW as the paper machine only used 64.5 MW of the steam produced from the refiners. The cooling demand of the mill was 26.8 MW [6].

The process integration (PI) was done through a pinch analysis resulting in an increase of 8.8 MW of the steam surplus and a decrease of 13.2 MW of the cooling demand, see Figure 33.

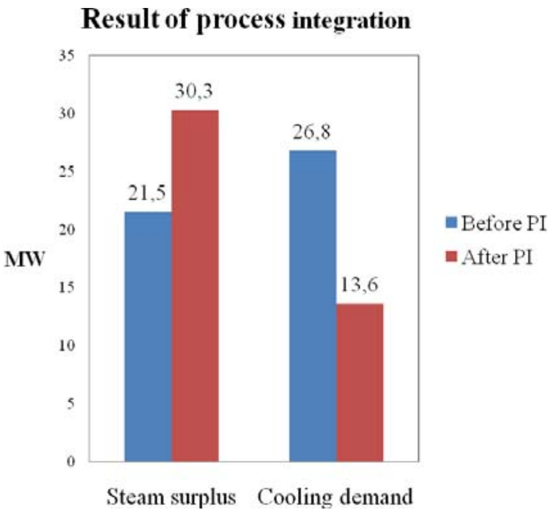

Figure 33 Result of the pinch analysi, model mill [6]

By solving pinch violations, in the pinch analysis, the heating demand could be reduced by 5.2 MW[33] and the cooling demand by 4.5 MW. Through preheating the dilution water to the refiner one could recover more steam from the refiners. Also if one preheated the impregnation water to the impregnation one would need less steam to the preheater after the impregnator. This both preheating measures would lead to a higher steam surplus plus a reduced cooling demand. The preheating was done by the process ventilation. The result was an increase of steam demand of 3.6 MW and a decrease of cooling demand of 2.6 MW. If the steam surplus, due to the reduced heating demand, could be exported the total reduction of the cooling demand would be 13.2 MW. After process integration the mill had a 41 % higher steam surplus (the heating demand is reduced by 14 %) and 49 % lower cooling demand [6].

Differences compared to the pulp and paper mill studied in this thesis are the plant size, the furnish composition, power demand, cooling demand, steam demand and production. Some of these differences are shown in Table 31. The most important difference between the real mill and the model mill is that the model mill is a whole pulp and paper mill but the real mill is only one paper machine and the corresponding pulp production.

The model mill was designed to have a steam surplus but as for the real mill it had instead a steam deficit. The model mill had a furnish composition of 70 % TMP, 12 % kraft[34] pulp and 30 % filler, therefore 58 % fibers [6]. In the base case of the real mill a pinch analysis was done, in this case the paper had a furnish composition of only fibers (TMP) and no DIP or filler. Later an analysis was done in two different future scenarios, in order to investigate the reduction in steam production. In the first scenario the furnish composition was 20 % DIP and 10 % filler. The second scenario was with the same furnish composition as in the first scenario but also with more energy efficient refining.

Table 31 Differences between Real mill and Model mill [6]

	Real mill		**Model mill**	
TMP production	177 360	ADt/year	272 000	ADt/year
Paper production	163 438	ADt/year	456 000	Ton
Power consumption	1 860	kW/ADt	3 050	kW/ADt
Steam production	16,8	MW	86	MW
Steam consumption	28,7	MW	64,5	MW
Excess of steam	-		21,5	MW
Deficit of steam	9,3	MW	-	

The results from this thesis are compared to the existing heating and cooling demand and compared to the results from Axelsson (2005). The comparison is first made between the retrofits solving pinch violations in the heat exchanger network separated from the other retrofits as the combinations between the retrofits are many. In the comparisons the heating demand refers to the clean steam demand. The comparison is presented in Figure 34.

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[33] The minimum temperature difference was violated in certain points in the new heat exchanger network, theoretical target was 3.4MW.

[34] Chemical wood pulp produced by digesting wood by the sulfate process.

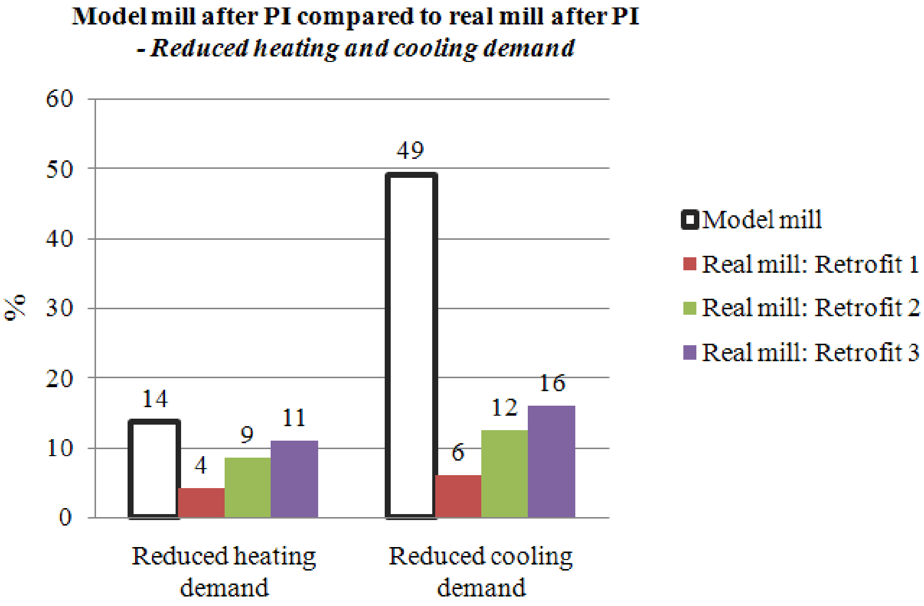

Figure 34 Comparison between results from the model mill after process integration and the real mill after process integration (only with retrofits solving pinch violations in the real mill).

Why the retrofit of the model mill gave a higher reduction in cooling demand can depend on several reasons, as all pulp and paper mills do not have identical processes. The difference between the pinch temperatures might also be one of the reasons. The pinch temperature of the model mill is 116.5 °C compared to 57.5 °C of the real mill. By having a higher pinch temperature more high temperature heat in the hot steams are released to heat the cold streams. One would think that as the real mill had a very high cooling demand this would be reduced more compared to the case of the model mill. But instead it showed that it had a much smaller decrease. However, this is not a bad result as Retrofit 3 reached a cooling demand of 15 MW when the minimum cooling demand was 13.2 MW. In the last retrofit, retrofit 3, the steam demand is reduced by 11% this is almost the same reduction as the one in the model mill, 14%. The reduction of cooling demand in retrofit 3 is closer to the one of the model mill but there is still a big difference.

A second comparison is made between the results from the model mill after process integration and the results from the real mill after process integration with the combinations of retrofits represented (except the Retrofits 1-3 alone which was shown in Figure 34). The comparison is shown in Figure 35. In the comparison the heating demand refers, as in Figure 34, to the clean steam demand.

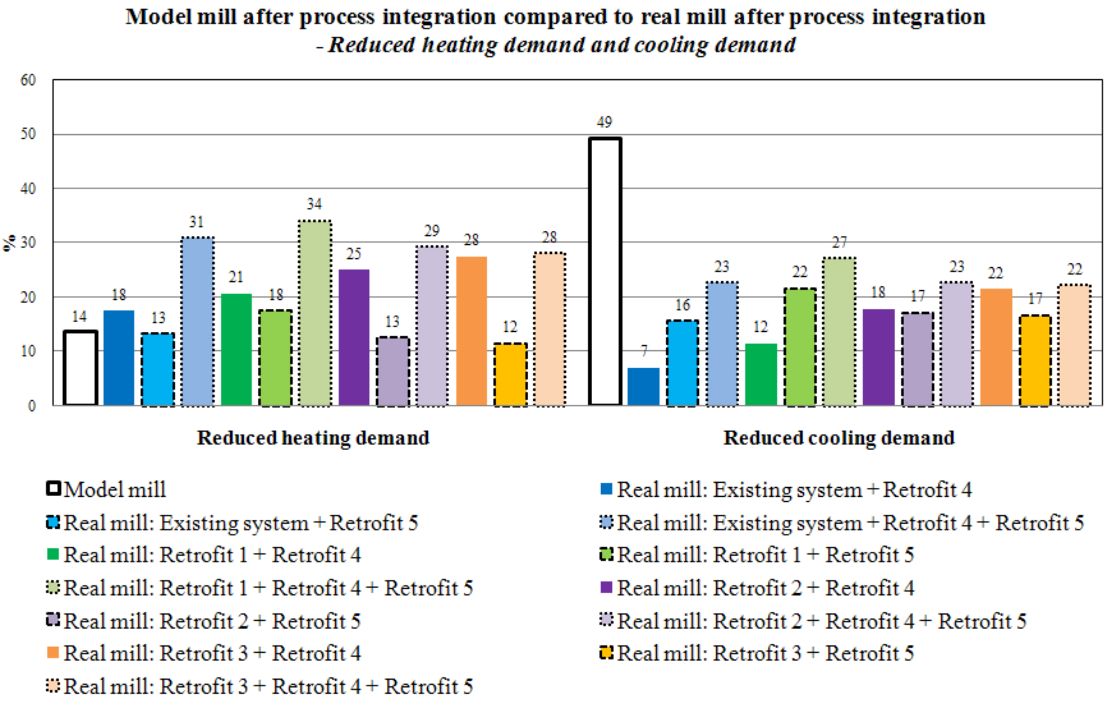

Figure 35 Comparison between results from the model mill after process integration and the real mill after process integration.

The reduction of heating demand and the cooling demand in the model mill is 14 % and 49 % respectively. The maximum reduction of heating demand and cooling demand in the real mill is 34 % and 27 % respectively. This shows that the results from process integration of a model mill can reach similar and even higher levels in a real mill, at least for the heating demand.

As the heating demand can be decreased, less steam is needed which can give a reduced steam deficit of the system or an increased steam surplus of the system. From the beginning the model mill had a steam surplus of 21.5 MW. In the real mill there is no steam surplus but a steam deficit of 9.3 MW. After process integration the steam surplus of the model mill was increased by 41 %, to 30.3 MW. In the real mill the steam deficit was reduced by 12 % to 96 % depending on the different retrofit solutions. The results and calculations in this section can be found in Appendix 14.

As a conclusion the comparison of the results from this thesis with a similar study of a TMP model mill showed that a part of a real mill, the studied system in this thesis, can reach even higher levels of steam savings than a model mill. However, the reduction of cooling demand was highest for the model mill compared to the real mill.

7.2 Error and sensitivity analysis

In a pinch analysis the data gathering plays an important role as the results depend on each stream’s temperature and flow. The uncertainties in the data gathering are presented in this section with a sensitivity analyzes of the pinch temperature. Furthermore, a sensitivity analysis of the future scenario with recycled paper and filler introduced is presented in the end of this section.

7.2.1 Uncertainties

The data from the model made by Norske Skog did not always agree with data from the controller screens or the mill's weekly energy reports. The reasons might be that the model was made one year ago and its focus was on the pulp and paper process and not on the energy system. For the work presented in this thesis, one important task was to find the steam consumers. Data for steam consumers in the model was double checked with printouts from the controller screens and also compared to the weekly energy reports. The steam data for PM1 was higher in the model than stated by the controller screens and energy reports. The steam consumption of the dryer in the model was 23.8 MW compared to 15.9 MW found in the energy report and from the controller screens. After discussion with Røstad[35], head of the boiler house, it was decided to use the real data instead of data from the model for the steam consumers. For general streams, which did not consume steam, flows and temperatures was taken from the model made by Norske Skog and the model made in Aspen HYSYS (described in Appendix 5).

Problems with the model was not only that it was incomplete, seen from an energy systems perspective, but also that it was lacking a lot of information about the cooling system of the plant and the usage of district heating. When gather information about the cooling a lot of estimations were made, based on discussion with operators and other employees at the mill. The reason behind the lack of cooling data in the model was probably due to the fact that cooling is cheap at a coast in Norway compared to a mill in a warmer country where cooling can be very expensive.

When analyzing the plant the analysis was done at steady state conditions. This included also the reboiler, no start-ups were occurring and all dirty steam should be used. The mill had been through a resent rebuild and the process was therefore not always stable. This was overcome by using data only from short stable periods.

The weekly energy reports contained information about the steam and district heating supply and use. The employees at the boiler house were aware that measurement instruments around the plant did not always deliver values that matched their energy balances. However, as this data was the most reliable and the used in all statistics of the energy supply and use at the mill it was the best available information.

The production of TMP and paper was based on the running time and data from the simulation model (FlowMac) made by Norske Skog. As the analysis was made in the spring of 2009 and not in the end of that year, the running time of the TMP plant had to be assumed. The assumed running time was the same as the planned running time of the paper plant which also was the same as the one the year before (2008). The paper production was calculated from the running time. The TMP plant was assumed to have the same running time as the paper plant. Based on the running time the TMP production was calculated. The calculations of the paper and pulp production can be found in Appendix 1.

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[35] Tormod Røstad (head of the boiler house at Norske Skog Skogn) interviewed 25 March 2009.

In assumption for the scenarios, the steam production in the TMP plant was reduced with the same amount of the reduction of TMP production. No other solution of a better approximation was found.

In the scenario with more energy efficient refining the electricity reduction of 5 % and 15 % are based from discussions with Lars Johansson at PFI (Paper and Fibre Research Institute). The percentages are general for a TMP plant and not further analysed.

7.2.2 Sensitivity analysis – Pinch temperature

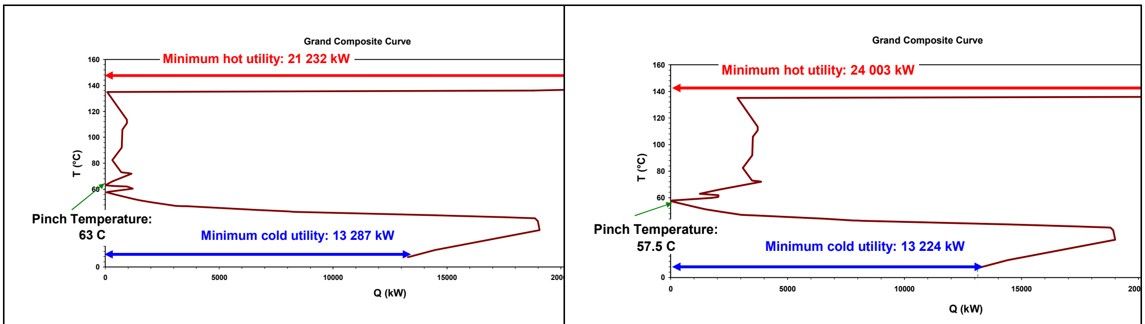
Additionally to the sources of error described above, the results were found to be sensitive to three of the streams analysed.

The three main streams that the pinch temperature and the pinch curves are sensitive to are:

Table 32 Streams that the pinch temperature is sensitive to.

Number of stream	Name	Type	Tstart [°C]	Ttarget [°C]	Q [kW]	ΔTmin/2 [°C]
32	Warm water	Cold	55	58	1520	2.5
36	White water from PM1	Cold	54	56	1341	3.5
37	White water continuation.	Cold	56	69	4273	3.5

The heat demand of these streams was varied and the effect on the pinch curves was analyzed. For the two streams of white water (streams 36-37), the heat loads were varied simultaneously as the second stream is a continuation of the first stream. The situation when the heat demand of these streams was smaller was studied. The heat demand was changed in such a way that it would resemble another TMP mill [6]. As the paper production of both mills was different, the heat demand was adjusted proportionally. The resulting GCC is shown on the left side in Figure 36. The original GCC is shown next to it (right side) for comparison purposes.



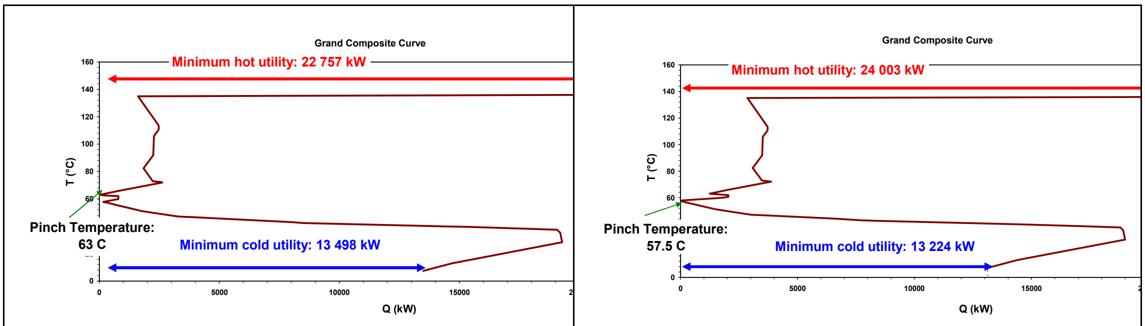
GCC if the white water heating demand is decreased

Original GCC

Figure 36 Sensitivity Analysis: Decreased white water heat demand

The two GCC curves show different characteristics. For the modified GCC the Pinch temperature is 63 ºC whereas the pinch temperature in the original case is 57.5 ºC. Moreover, the GCC shape gives the suggestion that the pinch temperature could even change to 135 ºC if the heat demand is further decreased. This variation in pinch temperature has an effect on the extra steam that can be produced by preheating opportunities. In section 5.5, it was described the possibility of producing more dirty steam if the dilution water to the refiners and/or the impregnation water was heated. It was also discussed that it was possible to preheat these streams only up to the pinch temperature without increasing the steam demand. If the pinch temperature was as high as 135 ºC, it would be possible to preheat these streams even further until the boiling point. This would in turn translate into 2844 kW more dirty steam generation than in the original case.

The sensitivity of the results was also investigated for changes to the warm water (stream 32). The extreme case in which this stream does not demand any heating was investigated. This stream forms part of a water circuit in PM1[36] for which there was nearly not information available and it was consequently consider being somewhat unreliable. The resulting GCC is presented in the left side of Figure 37, next to the original GCC (on the right).



GCC if the warm water does not demand any heating

Original GCC

Figure 37 Sensitivity Analysis: No warm water heat demand.

In this case the pinch temperature is 63 ºC but the differences in the curves are not as dramatic as in the case in which the white water streams (streams 36-37) were varied.

From both cases it is possible to conclude that the Pinch temperature is sensitive to changes in the streams discussed above and that it could vary among 57.5 ºC, 63 ºC and 135 ºC.

7.2.3 Sensitivity analysis – Future scenarios

In both studied scenarios the system is no longer the same as the existing system. In the first scenario, described in section 6.1, recycled paper and filler are introduced and as a consequence the TMP production is reduced by 30%. In the second scenario, described in section 6.2, additional to the new furnish composition, with 30% less TMP from the first scenario, the refining is more energy efficient. The reduction in

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[36] Please refer to section 3.3.2 for further description.

steam production is based on a reduction of 30% of the TMP production, as presented in sections 6.1-6.2. However, it is not only the steam production that is changed. As the TMP production is reduced all streams involved in the pulp production are also reduced. If this reduction is proportional to the reduction of TMP production the stream flows should be reduced with the same share, as the calculations of the decreased steam production was made. Note that the two scenarios have the same reduction of flow since the only difference between the scenarios are the more energy efficient refining which will not cause any changes to the liquid streams, only the steam flow is affected.

When comparing the reduced steam demand achieved in the retrofits against the steam deficit of the scenarios, presented in sections 6.1-6.2, it gets complicated. The pinch analysis with the resulting retrofits is made for the existing system as no stream data was available for the future scenarios. The question is if the retrofits are valid in a comparison against the scenarios with 30% less pulp production.

An analysis was made on the existing system to see how the minimum hot and cold utility would be changed if the streams related to the TMP production were reduced by 30%. The grand composite curve of the existing system and the future scenario, both the first and second scenario, is shown together in Figure 38.

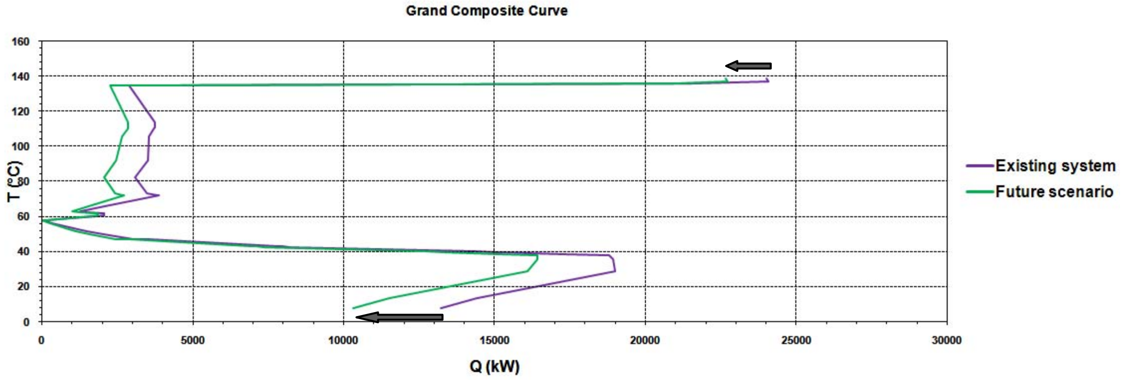

Figure 38 Grand composite curve of the existing system and the future scenario

The pinch temperature is in both cases 57.5°C but the minimum cold and hot utility have been reduced in the GCC of the future scenario (look at the arrows in the figure). The minimum hot and cold utility in the existing system are 24 003 kW and 13 224 kW respectively compared to 22 656 kW and 10 301 kW in the future scenario. The reduction is shown in Table 33 as difference.

Table 33 Minimum hot and cold utility for the existing situation and the future scenario [kW]

	Minimum hot utility [kW]	**Minimum cold utility [kW]**
Existing system	24 003	13 224
Future scenario	22 656	10 301
Difference	**1 347**	**2 923**

The fact that the reduction is larger for the minimum cold utility compared to the minimum hot utility is due to that the TMP production processes have a higher reduction of the cooling demand than heating demand.

The way the reduced TMP production would affect the retrofits solving only pinch violations could be that less heat from hot streams can be heat exchanged with cold streams that need heat, which leads to a decreased amount of heat recovered from the retrofits.

In Retrofit 1 the stream number 17 (other effluent from TM2B) is used to heat exchange with stream number 32 (warm water) which reduces the steam demand from 1520 kW to 1231 kW. In the future scenario stream number 17 is reduced by 30%, the steam demand for stream number 32 is reduced from 1520 kW to 1317 kW which is 86 kW less compared to the retrofit in the existing system. In the future scenario of Retrofit 2, the recovered heat is in the same way as in Retrofit 1 reduced by 86 kW. This is the same case in the future scenario of Retrofit 3. Furthermore, in Retrofit 3 stream number 15 (warm stream leaving TM2B) is affected and this leads to an increased steam usage of 20 kW.

As the pinch temperature is the same the preheating opportunities can still be implemented as described if there is enough waste heat (hot streams that need cooling). When analyzing the hot streams that were heat exchanged with the preheating opportunities, the heat is not enough to preheat both the dilution water to the refiners and the impregnation water. It is only enough to preheat one of them e.g. the dilution water. This would give 331 kW less additional steam. In both future scenarios the reboiler is running below its maximal capacity and therefore no new reboiler is needed. This is why the recovered steam from the scrubber is not included in Retrofit 4 shown in the summary of the heat recovery in Table 34. This steam is instead included in the steam production of the scenarios, presented in section 6.1-6.2.

After studying the GCC of the existing system and the future scenario the conclusion was that Retrofit 5, the heat pump configuration, would be affected by the reduction of TMP production. Figure 39 and Figure 40 show the GCCs of the existing system and the future scenario with the heat pump.

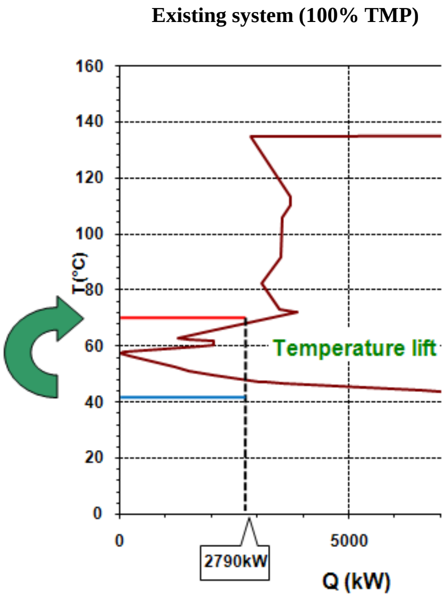

Figure 39 Heat pump in the existing system with 100% TMP

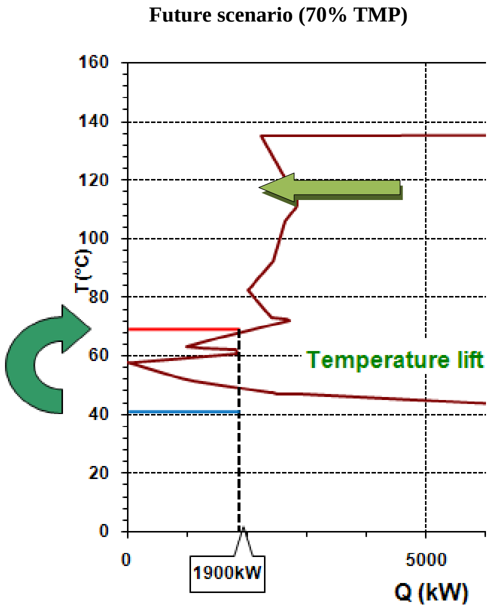

Figure 40 Heat pump in future scenario with 70% TMP

In the GCC of the existing system 2790 kW of steam could be saved, as described in section 5.6. However, in the future scenario the GCC is changed. The arrow illustrates how the GCC curve is moved closer to the temperature axis. From studying the GCC of the future scenario the amount of heat from the heat pump is reduced to about 1900 kW. The GCC illustrates how the studied system would look like if it had the minimum heating and cooling demand. As that is not the case in the existing system, more heat from the hot stream can be used, in Retrofit 5 (heat pump) 2.8 MW of heat is used and the heating demand is reduced by 3.5, described in section 5.6. In the future scenario the hot steam used by the heat pump is reduced by 30 % and therefore the heating demand is only reduced by 2.45 MW.

A summary of the heat recovery in the existing system and the future scenario is shown in Table 34, where it is also compared to each other.

Table 34 The heat recovery in the existing system compared to the heat recovery in the future scenario.

Retrofits	Heat recovery in existing system [MW]	Heat recovery in future scenario [MW]	Difference [MW]
Retrofit 1	1.082	0.996	0.086
Retrofit 2	2.222	2.136	0.086
Retrofit 3	2.867	2.761	0.106
Retrofit 4	0.840	0.509	0.331
Retrofit 5	3.503	2.452	1.051

In sections 6.1-6.2 a comparison between the deficit of steam production in the future scenarios and the surplus of steam from the retrofits on the existing system was made. In other words two systems which was not completely the same was compared to each other. The reason behind this inconsistent comparison is that there is no real information, other than the production of TMP, about how the system will change if these scenarios are put in place. This analysis was made in order to spot the main changes in heat recovery from the retrofits. The result from this analysis shows that Retrofit 5, the heat pump, is the retrofit which is most sensitive to the change in TMP production.

8 Conclusions

In this thesis a study of the energy situation of a part of a TMP mill was carried out. The thesis answers the main questions put forward in the objective (Chapter 1):

- *What is the current steam demand and steam production within the system?*

The system studied had a hot utility demand of 28.7MW and a cold utility demand of 17.9 MW.

- *How is the steam demand decreased by increased process integration?*

According to pinch analysis the minimum hot utility demand was 24.0 MW and the minimum cold utility demand was 13.2 MW. The maximum potential for savings of hot utility was therefore: 4.7 MW. The way the cooling of the refiners and DC motors is done was considered to be unchangeable and the maximum potential for steam savings was thus decreased to 3.3 MW.

    - *How much can the steam demand be reduced by improved internal heat exchange (solving pinch violations)?*

Three different retrofits were proposed. The first one aimed at decreasing pinch violations in the district heating system and 1.1 MW of hot utility savings were achieved. The second one aimed at decreasing pinch violations in the district heating system and modifying to some extent the paper machine heat recovery system, as a result 2.2 MW of hot utility savings were obtained. The third retrofit aimed at decreasing pinch violations in the district heating system and modifying drastically the paper machine heat recovery system. In this case, 2.9 MW of hot utility savings were achieved.

    - *What are the effects of increased preheating of suitable streams?*

By preheating suitable streams approximately 1.0 MW of excess dirty steam is possible to produce. However, a new reboiler with a larger capacity would be needed in order to convert it into clean steam. With a new reboiler 0.9 MW of clean steam could be produced. Additionally, the dirty steam that is currently sent to the scrubber could be recovered (3.8 MW of clean steam).

    - *What is the effect of integrating a heat pump in the system?*

Integrating a heat pump seemed to be a simple way to achieve large hot utility savings. For the existing network and in combination with Retrofit 1-3 it is possible to achieve savings between 0.2 MW and 3.5 MW by integrating heat pumps of different sizes.

It was possible to implement the preheating opportunities and the integration of a heat pump simultaneously with the existing network and Retrofits 1-3. In some cases, this translated into more than 8 MW of steam recovered.

- *How is the energy situation at the mill affected by a future introduction of recycled paper and filler? And how is the potential for increased process integration affected by this change?*

In a future scenario, when 20 % recycled paper and 10 % filler are introduced, the clean steam production will decrease more than the reduction of clean steam consumption in the retrofits solving pinch violations in the heat exchanger network (1.1 MW-2.9 MW). The clean steam production is reduced by 4.9 MW (19 %) including the reduction of steam from the boiler house that is reduced due to the reduction of bark. There is only one combination of retrofits which can meet up to the reduced steam production: the combination of Retrofit 1, the preheating opportunities (Retrofit 4) and the heat pump (Retrofit 5).

- *How is the energy situation at the mill affected by investments in more energy efficient refining? And how is the potential for increased process integration affected by this change?*

In a future scenario, when 20 % recycled paper and 10 % filler are introduced together with more energy efficient refining, the clean steam production is even further reduced. The reduction of clean steam production due to the pre-treatment of chips with or without higher refining intensity is 5.7 MW (22 %) and 8.0 MW (31 %) respectively. No combination of the retrofits can cover the steam production deficit of the scenarios with mechanical pre-treatment of chips with or without higher refining intensity.

The results from the scenarios presented in this study shows that by changing the composition furnish or by investing in more energy efficient refining the electricity consumption in the pulp plant is reduced. However, the reduction of electricity usage in the pulp mill can actually give an increased energy demand in another part of the mill. What is best is a question about economy and/or environment.

9 Further work

The recommendations of further work concerns the uncertainties of data, an economical and environmental study of the retrofits, reevaluating the results of the scenarios in the future and an energy system analysis of the scenarios.

The paper machine heat recovery system had to be simulated in Aspen HYSYS because lack of data, a measuring of the real flows and temperatures of the paper machine heat recovery system is recommended in order see if the simulated data matches the real ones.

This thesis has been focused on the potential of reducing the steam demand. The retrofits were presented with increasing complexity, this may indicate an increased investment, but no actual economical study was made. For further work an economical study is highly recommended. Also an analysis of the environmental effects of the retrofits is suggested.

In the scenario with the introduction of recycled paper and filler, the calculations were based on the reduced TMP production. It is important to remember that the results can not be used without a reevaluation in the future, when the recycled paper and filler are introduced. However, this analysis can be used as a guidance and point out a general direction.

An energy system analysis should be carried out in order to answer the question of what is most favorable in the environmental and economical aspect when reducing the electricity demand presented in the scenarios.

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Appendix

Appendix 1 – The production of thermo mechanical pulp (TMP) and paper
Appendix 2 – Steam consumption and production in the studied system
Appendix 3 – The heating demand and cooling demand
Appendix 4 – Energy use
Appendix 5 – Paper machine heat recovery system simulation in Aspen HYSYS
Appendix 6 – District heating system
Appendix 7 – Calculations of preheating of dilution water to the refiners
Appendix 8 – Calculations of preheating of impregnation water
Appendix 9 – The reboiler
Appendix 10 – Preheating opportunities and new reboiler
Appendix 11 – Heat pump
Appendix 12 – Combinations of retrofit proposals
Appendix 13 – Calculations of the future scenarios
Appendix 14 – Calculations of the comparison of the results with a similar study of a TMP model mill

Appendix 1 – The production of thermo mechanical pulp (TMP) and paper

The production of thermo mechanical pulp (TMP) and paper in the studied system, TM2B and PM1, was based on the production speed in the simulated model (FlowMac) made by Norske Skog. The production speed in BDkg/s is presented in the table below.

Speed in TMP and paper plant	**TM2B – pulp**	**PM1 – paper**
BDkg/s	5,86	5,4

To convert the speed into ADkg/s, it was multiplied by 1.1. The production speed in ADkg/s is presented in the table below.

Speed in TMP and paper plant	**TM2B – pulp**	**PM1 – paper**
ADkg/s	6,446	5,94

The planned running time of PM1 is 7643 hours per year and the same running time was used for the TMP plant TM2B. When calculating the production per year the running time and the production speed was used.

Production [kg/yr] = running time [h/yr] × production speed [kg/s] × 3600 [s/h]

The production of TMP and paper is shown in the table below, in both BDt/yr and ADt/yr.

Production of TMP and paper	**TM2B – pulp**	**PM1 – paper**
BDt/yr	161 237	148 580
ADt/yr	177 360	163 438

Appendix 2 – Steam consumption and production of the studied system

In this appendix the calculations of steam consumption and production, presented in Table 4 in section 3.2, are shown below. The loads are calculated below the table.

Steam production and consumption

Steam users	**Load [MW]**
Press section (steam box)	1,9[1]
Dryer	15,9[2]
Air to dryer	1,6[3]
Calender	0,9[4]
Hot water	1,5[5]
Steaming	0,6[6]
Preheating	2,0[7]
Hot dilution water	4,3[8]
Total demand	**28,7**
Production - clean steam	16,8[9]
Production - dirty steam	6,8[10]
Deficit of clean steam	**9,3**
Surplus of dirty steam	**4,3**

Load (Q) = mass flow (m) × enthalpy difference (Δh)

1) From controller screen. Steam consumption: 0.84 kg/s. Pressure: 2.12 bar (a). Steam temperature: 141.8˚C. The pressure and temperature gives the enthalpies: enthalpy (vapour): 2750.75kJ/kg and enthalpy (liquid): 512.72kJ/kg. The load of the steam box is: Q=0.84*(2750.75-512.72)/1000=1.89MW.

2) From controller screen. Steam consumption: 7.34 kg/s. Pressure: 3.29 bar (a). Steam temperature: 141.8˚C. The pressure and temperature gives the enthalpies: enthalpy (vapour): 2740.74kJ/kg and enthalpy (liquid): 575kJ/kg. The load of the steam box is: Q=7.34*(2740.74-575)/1000=15.9MW.

3) From simulation model in Aspen HYSYS. Two steam heaters of the air to dryer (stream numbers 20-23): 824kW and 742.2kW, together 1.5662 MW.

(4) From controller screen. Steam consumption: 0.436 kg/s. Pressure: 3.29 bar (a). Steam temperature: 141.8˚C. The pressure and temperature gives the enthalpies: enthalpy (vapour): 2740.74kJ/kg and enthalpy (liquid): 575kJ/kg. The load of the steam box is: Q=0.436*(2740.74-575)/1000=0.945MW.

(5) From the weekly energy report of the mill (12/ 2009). Energy in steam for one week: 221.8MWh. Assumed running time (as the production of paper 2008): 7589h/yr. This gives the running time per week: 146h/week. The load is calculated by dividing the energy by the running time. Q=221.8/146=1.5MW.

(6) From simulation model (FlowMac) of the mill made by Norske Skog. Steam consumption: 0.26 kg/s. Pressure: 3.2 bar (a). Steam temperature: 134˚C. The pressure and temperature gives the enthalpies: enthalpy (vapour): 2728kJ/kg and enthalpy (liquid): 570kJ/kg. The load of the steam box is: Q=0.26*(2728-570)/1000=0.561MW.

(7) From simulation model (FlowMac) of the mill made by Norske Skog. Steam consumption: 0.93 kg/s. Pressure: 3.2 bar (a). Steam temperature: 134˚C. The pressure and temperature gives the enthalpies: enthalpy (vapour): 2728kJ/kg and enthalpy (liquid): 570kJ/kg. The load of the steam box is: Q=0.93*(2728-570)/1000=2.007MW.

(8) From simulation model (FlowMac) of the mill made by Norske Skog and from discussions with employees of the mill. The heater used only clean steam. In FlowMac the steam was dirty. In this study the steam was calculated as clean steam as in reality but the same load as in FlowMac was used. The data from FlowMac: steam consumption: 1.98 kg/s. Pressure: 3.2 bar (a). Steam temperature: 134˚C. The pressure and temperature gives the enthalpies: enthalpy (vapour): 2728kJ/kg and enthalpy (liquid): 570kJ/kg. The load of the steam box is: Q=1.98*(2728-570)/1000=4.273MW.

(9) From a capacity test of the reboiler: of three loads presented the one in the middle was used in this study, 16.8MW.

(10) From simulation model (FlowMac) of the mill made by Norske Skog. Steam production: 3.17 kg/s. Pressure: 3.2 bar (a). Steam temperature: 134˚C. The pressure and temperature gives the enthalpies: enthalpy (vapour): 2728kJ/kg and enthalpy (liquid): 570kJ/kg. The load of the steam box is: Q=3.17*(2728-570)/1000=6.841MW.

Appendix 3 – The heating demand and cooling demand

In this appendix the heating demand and cooling demand, presented in Table 2 and Table 3 in section 3.2, are presented more in detail.

- **The heating demand of the studied system is:**

Total heating demand

Hot utility	**Load [MW]**
Clean steam	26,1[1]
Dirty steam	2,6[2]
Total heating demand	**28.7**

[1] The total steam demand, 28.7 MW, minus the dirty steam consumption of 2.6 MW.

[2] The dirty steam consumption is the steaming (0.6 MW) together with the preheating (2 MW) described in Appendix 2.

- **The cooling consumers of the studied system are:**

Total cooling demand

Cold utility	**Load [MW]**
Refiner cooling	0.5[3]
Motor cooling	0.9[4]
Effluent cooling	8.5[5]
Other cooling	8.0[6]
Total cooling demand	**17.9**

[3] Water is used to cool the air in the motor house. The water is kept at 15 °C and the motor air is thereby kept at around 80 °C (81 °C → 80 °C). After, the water is send to a chest used to heat the dilution water to the refiners. In the model of the mill (Flow Mac) made by Norske Skog, the cooling of the refiners was 1035 kW, of this 45 % was the cooling of the refiners within the studied system; 461 kW. Additional to the cooling of the motor air there is cooling of an oil circuit, used to cool the bearings in the refiner. This circuit is cooled from 60 °C to 40 °C with a flow of 0.45 kg/s, resulting in a load of: (60-40) [°C] *0.45 [kg/s] *2.13 [kJ/kgK] =19 kW. The total refiner cooling is: 19 + 461 = 480 kW.

[4] The DC motors that are running the PM1 (wire section, drying section) is not self cooled. Air at temperature 23 °C is added to make the motor air keep the temperature of about 70 °C, the cooling air is exiting at a temperature of 55 °C. The total flow for all motors was assumed (with help from Kertil Røe, employee at Norske Skog Skogn and in charge of the electric motors at the plant) to be 25m^3/s. Therefore, the total motor cooling (with air) was: 25 [m^3/s]*1.005 [kJ/kgK]*1.127 [kg/m^3]* (55-23) [˚C] = 906 kW.

[5] All effluent streams that need to be cooled down to 32 ˚C are included in this value. The streams are: stream 15 (warm stream leaving TM2B) – 4.269 MW, stream 16 (water from chip wash) – 0.499 MW, stream 17 (other effluent from TM2B) – 1.275 MW, stream 18 (warm clear filtrate from chest (PM1)) – 2.287 MW and stream 19 (effluent from PM1) – 0.201 MW. This gives a total cooling demand of 8.531 MW.

[6] The other cooling refers to the cooling made by water (the refiner cooling and the effluent water cooling is not included here). This was an estimation made by an old mass balance done in 2006, Figure 3 in the beginning of Chapter 3, and the assumed running time of 7643 hours per year. In the mass balance the fresh water intake was 31 743 850 tonnes (1154 l/s). Of this 6 108 286 tonnes (222 l/s) was process water, data from the model of the mill (Flow Mac) made by Norske Skog. The remaining part, 25 635 564 tonnes (932 l/s), was cooling water and sealing water. Of this some cooling water was used in the effluent treatment plant (380 l/s, 10 455 624 tonnes), in the DIP (deinking plant, recycled paper) plant (100 l/s, 2 751 480) and as sealing water (25 l/s, 687 870). The remaining part of this, called other cooling water, was 11 740 590 tonnes (427 l/s). The cooling water within the studied system was assumed, based on the production rates at the different plants, to be 173 l/s. The cooling load was calculated with the assumed temperatures: intake temperature of 4 ˚C and an exit temperature of 15 ˚C. The cooling demand for other cooling in the studied system was: 173 [l/s]*(15-4) [˚C]*4.18 [kJ/kgK] = 7 963 kW = 8 MW.

Appendix 4 – Energy use

The energy supply and use of the mill is based on the mill's energy report from 2008 and for the system studied in this thesis the data was based on information from controller screens.

Steam production and consumption

The mill

The total steam production is presented in the table below.

Data from energy report 2008

Total steam production	[MWh]	[%]
Energy from boilers	359 991	47,5%
Energy from TM1	87 844	11,6%
Energy TM2	289 904	38,2%
Energy from Oil boiler	12 599	1,7%
Energy from el. boiler	8 175	1,1%
Total energy	**758 513**	100%
Steam from all boilers:	380 765	50.2%
Steam from TMP production:	377 748	49.8%

The total steam consumption of the mill is presented in the table below.

Data from energy report 2008

Total steam consumption:	**750 022 MWh**

The system

Within the system boundaries of the studied system, the steam production is based on the capacity tests of the reboiler. The steam production of the system in presented in the table below.

Steam production	[MW]	[MWh]
In the pulp plant - TM2B	16.8	**128 402**

The steam consumption of the system is based on the steam consumption table presented in Appendix 2. The steam consumption of the system is presented in the table below.

Steam consumption in the existing system	[MW]	[MWh]
PM1	21.81	166 704
TM2B	4.27	32 657
Total	26.08	**199 361**

District heating production and consumption

The mill

The district heating production of the mill is based on the energy report from 2008. The total district heating production is presented in the table below.

Data from energy report 2008

Total district heating production	[MWh]	[%]
From heat recovery in TMP plants	73 711	64%
From the boiler house	42 006	36%
Total production	**115 717**	100%

The district heating consumption of the mill is based on the energy report from 2008. The total district heating consumption is presented in the table below.

Data from energy report 2008

Total district heating consumption	**115 717 MWh**

The system

Within the studied system the production of district heating (DH) is based on data from the simulation model (FlowMac) made by Norske Skog and a running time of 7643 hours per year. The district heating production is presented in the table below.

DH production in our SB	[MW]	[MWh]
TM2B - dirty condensate	2.21	**16 891**

The consumption of district heating in the system is based on the simulation model in Aspen HYSYS described in Appendix 5 and a running time of 7642 hours per year. The district heating consumption of the system is presented in the table below.

DH consumption in our SB	[MW]	[MWh]
PM1 - air for mix	0.7932	6 062
PM1 - air to drying	0.7961	6 085
Total consumption	1.5893	**12 147**

Electricity production and consumption

The mill

The total electricity production at the mill is generated from a steam turbine. The electricity production is presented in the table below.

Data from energy report 2008

Production of electricity	[MWh]
Turbine	**33 960**

The total consumption of electricity in 2008 is presented in the table below.

Data from 2008 (Tormod Røstad) Norske Skog Skogn

Total consumption of electricity	**1255 GWh**

The system

There is no electricity production within the studied system. The total electricity consumption of the system is not presented however the electricity consumption of the refining is presented. The calculations can be seen in the calculations below. The electricity consumption of the refining is presented in the last table.

Data of the refiners in the system, from the simulated model (FlowMac) made by Norske Skog.

	[kWh/BDt]
refiner 1 stage	1077
refiner 2 stage	695
LC-refiner 1	137
LC-refiner 2	137
Total	2046

Convert into kWh/ADt -> divide with 1.1

2046 kWh/BDt 2046/1.1=**1860** kWh/ADt

Running time of TMP plant:		7643	hours/year
Pulp/chips speed:		5,5	BDkg/s (refiners)
Chips through refiners per year:	7643*1.1*5.5*3600/1000 =	166 464	ADt/year

Electricity consumption of the refining = 166 464*7643 = 309 624 044 GWh = **309,6** GWh

Data from calculations above

Electricity consumption of refining	**309.6GWh**

Appendix 5 – Paper machine heat recovery system simulation in Aspen HYSYS

Simulations in Aspen HYSYS

The data of the air from the dryer heat recovery system was not complete in the FlowMac model. It was therefore modelled in the process simulation program Aspen HYSYS.

The temperatures were taken from the controller screen (2009-03-20) presented in the table below.

Stream	**Temperature [˚C]**
Air to the dryer (stream 20), before the district heating heater	46.5
Air to the dryer (stream 21), before the district heating heater	46.1
Air to the dryer (stream 22), before the district heating heater	48.1
Air to the dryer (stream 23), before the district heating heater	48.1
Air to the dryer (streams 20-21), before the steam heater	66.4
Air to the dryer (streams 22-23), before the steam heater	65.5
Air to the dryer (stream 20-21), to drying hood	103.1
Air to the dryer (stream 22-23), to drying hood	102.5
Air from dryer exits the drying hood nr 1	64.4
Air from dryer exits the drying hood nr 2	68.5
Air from dryer exits the drying hood nr 3	115.1
Air to dryer (streams 20-23), before the heat exchanger with air from dryer (streams 1-8)	41.7
Average target temperature of Air for mix (streams 24-27)	35
Fresh water (stream 28) after heat exchanger with air from dryer (stream 1)	33
Fresh water (stream 29) after heat exchanger with air from dryer (stream 2)	41.6
Fresh water (stream 30) after heat exchanger with air from dryer (stream 3)	44.2
Fresh water (stream 31) after heat exchanger with air from dryer (stream 4)	44.5

The outdoor temperature and the fresh water temperature was 5˚C.

The flow rates of fresh water (streams 28-31) were taken from the controller screens, presented in the table below.

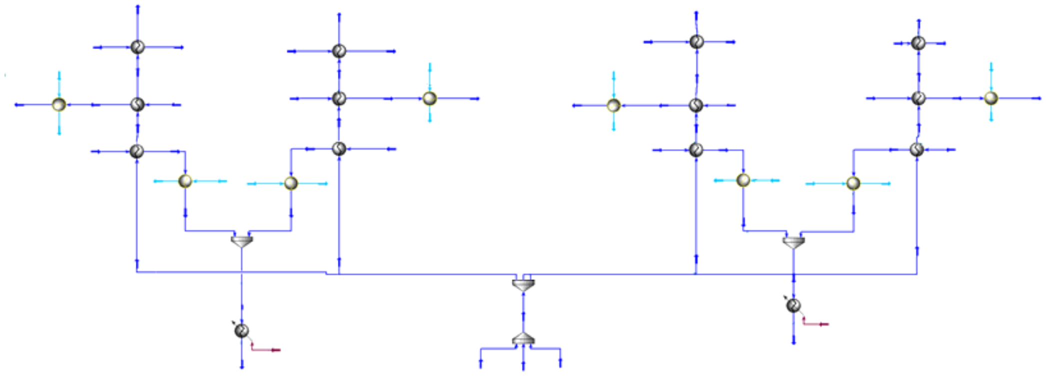
Stream	Flow rate [kg/s]
Fresh water (stream 28)	11.8
Fresh water (stream 29)	13.2
Fresh water (stream 30)	12.6
Fresh water (stream 31)	14

The flow rates of the air from dryer (nr 1, 2 and 3) and of the air to dryer (stream 20-23) were taken from an internal report (2008-02-13), where information about the water content of the steams was also available. The flow rates was measured one year ago but was assumed to be valid in the current situation. In the table below the flow rates are presented together with the water content of the steams.

Stream	Flow rate [kg dry air/s]	Water content [gH_2O/kg]
Air from dryer nr 1	14.3	108
Air from dryer nr 2	21.5	109
Air from dryer nr 3	33.3	122
Air to dryer (stream 20-21 together)	21.6	20
Air to dryer (stream 22-23 together)	19.3	20

The total flow rate of the air for mix (streams 24-27), 80 kg/s, was taken from FlowMac. It was assumed to be the same flow rate in the four streams (20kg/s).

The heat recovery system was then modelled in Aspen HYSYS. A picture of the model can be seen below.

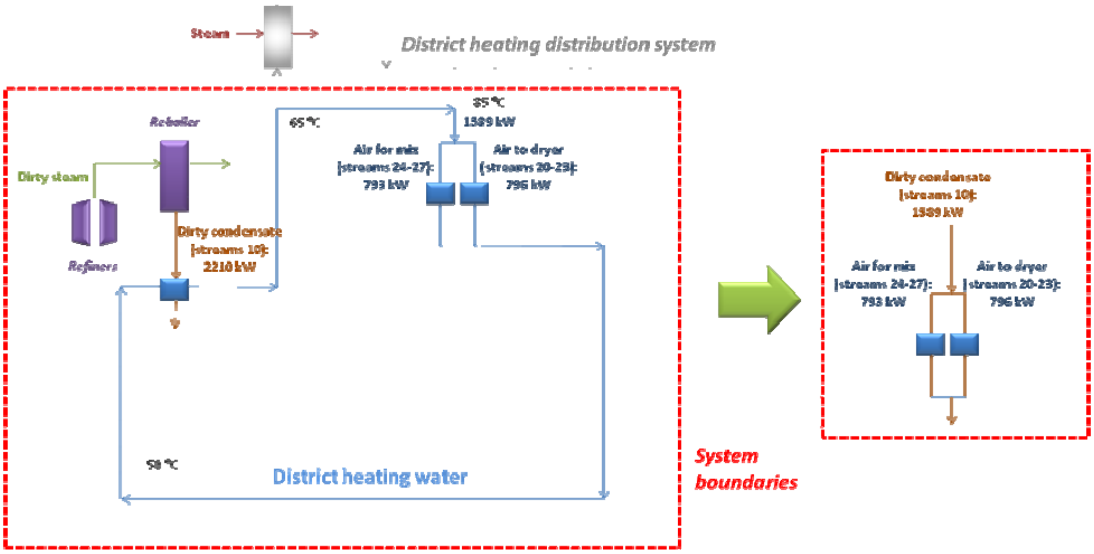


The fluid package used for the simulation was PP: NRTL-Ideal. In this model, the air from dryer (streams 1, 3, 5, 7) begins to condensate when it heats the fresh water (streams 28-31), the last heat exchangers. As the heat capacity of the condensing streams (streams 2, 4, 6, 8) varies significantly respect the non-condensing streams, a distinction was made between them. The results from the simulation are presented in the following table.

Unit	Load [kW]
Heat exchanger (stream 1 with stream 20)	53.5
Heat exchanger (stream 3 with stream 21)	49.2
Heat exchanger (stream 5 with stream 22)	63.7
Heat exchanger (stream 7 with stream 23)	63.7
Heat exchanger (stream 1 with stream 24)	395.5
Heat exchanger (stream 3 with stream 25)	395.5
Heat exchanger (stream 5 with stream 26)	395.5
Heat exchanger (stream 7 with stream 27)	395.5
Heat exchanger (stream 1&2 with stream 28)	1385
Heat exchanger (stream 3&4 with stream 29)	2029
Heat exchanger (stream 5&6 with stream 30)	2075
Heat exchanger (stream 7&8 with stream 31)	2323
DH heater (stream 24)	198.3
DH heater (stream 25)	198.3

DH heater (stream 26)	198.3
DH heater (stream 27)	198.3
DH heater (stream 20)	222.2
DH heater (stream 21)	226.7
DH heater (stream 22)	173.6
DH heater (stream 23)	173.6
Steam heater (stream 20&21)	824
Steam heater (stream 22&23)	742.2

Appendix 6 – District heating system



The district heating system is a common system for the entire mill. It consist of a hot water circuit that is used to heat different streams in the mill e.g. the air for mix (streams 24-27) and air to dryer (streams 20-23). The district heating water is heated at different places of the mill e.g. by the dirty condensate (stream 10) and with steam.

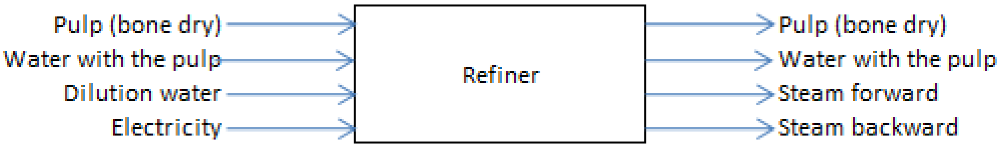
The district heating consumers within the system boundaries of this pinch analysis demand 1589 kW of district heating water at 85°C. The dirty condensate on the other hand produces 2210 kW of district heating water at 65°C. Since this is too cold to be used, the district heating water is heated up to 85°C with steam. The following simplifications were made in order to model de district heating system.

1. The dirty condensate (stream 10) must always export 621 kW (2210 kW-1589 kW) to the district heating system and can be therefore modelled as a stream with 621 kW less heat available than in reality. In this way, the suggested modifications in the retrofits will not affect the other systems outside the system boundaries.
2. If the demand of district heating within the system is decreased, there is no need to use the heat available in the dirty condensate (stream 10) for preheating that amount water. The dirty condensate can be used instead to export heat to the district heating system and reduce in this way the use of steam.
3. For the pinch analysis it is possible to represent this arrangement with various heat exchangers in which the dirty condensate (stream 10) transfers heat to the air to dryer (streams 20-23) and to the air for mix (streams 24-27).
4. For the retrofit proposals, if the heating of the air streams can be achieved in a different way, then the dirty condensate can heat streams above the pinch e.g. white water (stream 37) reducing in this way the pinch violations.

For all the network representations presented in Chapter 4-5, the district heating system is illustrated as a cooler in the dirty condensate and as heaters in the air to dryer and air for mix. This is done only with the purpose to present neat figures. However, the district heating system was actually modelled as heat exchangers as mentioned in point 3 above and as illustrated in the figure above.

Appendix 7 – Calculations of preheating of dilution water to the refiners

The steam recovered through preheating of the dilution water was calculated by doing mass and energy balances around the two high consistency refiners (refiner 27 and refiner 28). The streams considered for the energy balance are shown below.



The heat capacity of the bone dry pulp was estimated from wood heat capacity correlations [16]:

$$\text{Heat capacity of wood}\left[\frac{kJ}{kg\,K}\right] = 0.1031 + 0.003867\,T\,[°C]$$

Steam tables were used to estimate the specific enthalpy of water.

The mass and energy balance for refiner 27 is shown in Table 35.

Table 35 Mass and energy balances around refiner 27, dilution water temperature 44˚ C.

IN	
Pulp (bone dry)	
Flowrate [kg/s]	5.6
Temperature [C]	120
Pressure [barg]	2
Enthalpy [kJ/kg]	175
ENERGY FLOW [kW]	980
Water with the pulp	
Consistency [%]	55
Flowrate [kg/s]	4.6
Temperature [C]	120
Pressure [barg]	2
Enthalpy [kJ/kg]	504
ENERGY FLOW [kW]	2 309
Dilution water	
Flowrate [kg/s]	7.71
Temperature [C]	44.26
Pressure [barg]	2
Enthalpy [kJ/kg]	186
ENERGY FLOW [kW]	1 432
Electricity	
Gr. Spec Energy [kWh/t]	932
ENERGY FLOW [kW]	18 785
TOTAL ENERGY IN [kW]	23 506

OUT	
Pulp (bone dry)	
Flowrate [kg/s]	5.5
Temperature [C]	155
Pressure [barg]	4.5
Enthalpy [kJ/kg]	226
ENERGY FLOW [kW]	1 244
Water with the pulp	
Consistency [%]	50
Flowrate [kg/s]	5.5
Temperature [C]	155
Pressure [barg]	4.5
Enthalpy [kJ/kg]	654
ENERGY FLOW [kW]	3 597
Steam forward	
Flowrate [kg/s]	4.77
Temperature [C]	155
Pressure [barg]	4.5
Enthalpy [kJ/kg]	2753
ENERGY FLOW [kW]	13 128
Steam backward	
Flowrate [kg/s]	2.03
Temperature [C]	139
Pressure [barg]	2.5
Enthalpy [kJ/kg]	2733
ENERGY FLOW [kW]	5 537
TOTAL ENERGY OUT [kW]	23 506

The additional steam produced when the dilution water is heated to 55 °C was calculated by solving simultaneously the water balance (more water is needed in order to produce more steam) and the energy balance (more heat is needed to preheat the water). It was assumed that the proportion of forward and backward steam remained constant (70% forward steam, 30% backward steam). The balances are shown in Table 36.

Table 36 Mass and energy balances around refiner 27, dilution water temperature 55 ˚C

IN		**OUT**	
Pulp (bone dry)		***Pulp (bone dry)***	
Flowrate [kg/s]	5.6	Flowrate [kg/s]	5.5
Temperature [C]	120	Temperature [C]	155
Pressure [barg]	2	Pressure [barg]	4.5
Enthalpy [kJ/kg]	175	Enthalpy [kJ/kg]	226
ENERGY FLOW [kW]	980	ENERGY FLOW [kW]	1 244
Water with the pulp		***Water with the pulp***	
Consistency [%]	55	Consistency [%]	50
Flowrate [kg/s]	4.6	Flowrate [kg/s]	5.5
Temperature [C]	120	Temperature [C]	155
Pressure [barg]	2	Pressure [barg]	4.5
Enthalpy [kJ/kg]	504	Enthalpy [kJ/kg]	654
ENERGY FLOW [kW]	2 309	ENERGY FLOW [kW]	3 597
Dilution water		***Steam forward***	
Flowrate [kg/s]	**7.84**	**Flowrate [kg/s]**	**4.86**
Temperature [C]	**55**	Temperature [C]	155
Pressure [barg]	2	Pressure [barg]	4.5
Enthalpy [kJ/kg]	**228**	Enthalpy [kJ/kg]	2753
ENERGY FLOW [kW]	**1 792**	**ENERGY FLOW [kW]**	**13 381**
Electricity		***Steam backward***	
Gr. Spec Energy [kWh/t]	932	**Flowrate [kg/s]**	**2.07**
ENERGY FLOW [kW]	18 785	Temperature [C]	139
		Pressure [barg]	2.5
		Enthalpy [kJ/kg]	2733
		ENERGY FLOW [kW]	**5 644**
TOTAL ENERGY IN [kW]	**23 867**	**TOTAL ENERGY OUT [kW]**	**23 867**

Additional 253 kW (13381 kW-13128 kW) of forward steam is produced if the dilution water entering the refiner 27 is preheated. Additional 107 kW (5644 kW-5537 kW) of backward steam is produced.

In a similar way mass and energy balances were made for the refiner 28. The balances for the case in which the dilution water enters the refiner at 44 °C are presented in Table 37.

Table 37 Mass and energy balances around refiner 28, dilution water temperature 44 C

IN		**OUT**	
Pulp (bone dry)		***Pulp (bone dry)***	
Flowrate [kg/s]	5.5	Flowrate [kg/s]	5.5
Temperature [C]	143	Temperature [C]	155
Pressure [barg]	3.4	Pressure [barg]	4.5
Enthalpy [kJ/kg]	209	Enthalpy [kJ/kg]	226
ENERGY FLOW [kW]	1 148	ENERGY FLOW [kW]	1 244
Water with the pulp		***Water with the pulp***	
Consistency [%]	45.11	Consistency [%]	44.11
Flowrate [kg/s]	6.7	Flowrate [kg/s]	7.0
Temperature [C]	143	Temperature [C]	155
Pressure [barg]	3.4	Pressure [barg]	4.5
Enthalpy [kJ/kg]	602	Enthalpy [kJ/kg]	654
ENERGY FLOW [kW]	4 030	ENERGY FLOW [kW]	4 558
Dilution water		***Steam forward***	
Flowrate [kg/s]	4.70	Flowrate [kg/s]	3.10
Temperature [C]	44.26	Temperature [C]	155
Pressure [barg]	3.4	Pressure [barg]	4.5
Enthalpy [kJ/kg]	186	Enthalpy [kJ/kg]	2753
ENERGY FLOW [kW]	873	ENERGY FLOW [kW]	8 540
Electricity		***Steam backward***	
Gr. Spec Energy [kWh/t]	601.2	Flowrate [kg/s]	1.32
ENERGY FLOW [kW]	11 916	Temperature [C]	148
		Pressure [barg]	3.5
		Enthalpy [kJ/kg]	2744
		ENERGY FLOW [kW]	3 625
TOTAL ENERGY IN [kW]	17 967	**TOTAL ENERGY OUT [kW]**	17 967

The balances for the case in which the dilution water is preheated to 55 °C are presented in Table 38.

Table 38 Mass and energy balances around refiner 28, dilution water temperature 55 ˚C

IN		**OUT**	
Pulp (bone dry)		***Pulp (bone dry)***	
Flowrate [kg/s]	5.5	Flowrate [kg/s]	5.5
Temperature [C]	143	Temperature [C]	155
Pressure [barg]	3.4	Pressure [barg]	4.5
Enthalpy [kJ/kg]	209	Enthalpy [kJ/kg]	226
ENERGY FLOW [kW]	1 148	ENERGY FLOW [kW]	1 244
Water with the pulp		***Water with the pulp***	
Consistency [%]	45.11	Consistency [%]	44.11
Flowrate [kg/s]	6.7	Flowrate [kg/s]	7.0
Temperature [C]	143	Temperature [C]	155
Pressure [barg]	3.4	Pressure [barg]	4.5
Enthalpy [kJ/kg]	602	Enthalpy [kJ/kg]	654
ENERGY FLOW [kW]	4 030	ENERGY FLOW [kW]	4 558
Dilution water		***Steam forward***	
Flowrate [kg/s]	**4.78**	**Flowrate [kg/s]**	**3.16**
Temperature [C]	**55**	Temperature [C]	155
Pressure [barg]	3.4	Pressure [barg]	4.5
Enthalpy [kJ/kg]	**228**	Enthalpy [kJ/kg]	2753
ENERGY FLOW [kW]	1 092	**ENERGY FLOW [kW]**	**8 694**
Electricity		***Steam backward***	
Gr. Spec Energy [kWh/t]	601.2	**Flowrate [kg/s]**	**1.34**
ENERGY FLOW [kW]	11 916	Temperature [C]	148
		Pressure [barg]	3.5
		Enthalpy [kJ/kg]	2744
		ENERGY FLOW [kW]	**3 690**
TOTAL ENERGY IN [kW]	**18 185**	**TOTAL ENERGY OUT [kW]**	**18 185**

Additional 154 kW (8698 kW-8540 kW) of forward steam is produced if the dilution water entering the refiner 28 is preheated. Additional 65 kW (3690 kW-3625 kW) of backward steam is produced.

Overall, considering the two refiners and the forward and backward steam, it is possible to produce 579 kW of dirty steam (253 kW+154 kW+107 kW+65 kW). Assuming that the reboiler has a bigger capacity and an efficiency of 87.9%, the clean steam produced is 509 kW (579 kW*0.879).

Appendix 8 – Calculations of preheating of impregnation water

The preheating of the impregnation and its consequences as; decreased steam demand in the preheater, the decreased cooling demand and the amount of heating needed for the preheating is presented in this appendix. Before refers to before any preheating of impregnation water (the temperature of the impregnation water is 10˚C) and after refers to that the impregnation water is preheated (the temperature of the impregnation water is 55˚C).

The incoming wood chips to the impregnation tower have a consistency of 40% and a temperature of 70˚C. The energy is calculated from the formula:

Q [kW] = cp [kJ/kgK]*T [˚C]*massflow [kg/s]

The heat capacity for water is between 4.18-4.23 kJ/kgK dependent on the temperature of the water and the heat capacity of the wood chips was assumed to be between 1.38-1.62 kJ/kgK dependent on temperature. The formula for the heat capacity of wood chips can be found in Appendix 7.

Impregnation tower:

BEFORE preheating	in	Out
Consistency [%]	40	30
Total flow [kg/s]	15	19
Fiber flow [BDkg/s]	5,6	5,6
Water flow [kg/s]	9	9
Impr. Water flow [kg/s]	4	4
Energy chips [kW]	3330	2670
Energy impr water [kW]	168	945
Total energy [kW]	3498	3614
Error [kW]	116	
Temp in of impr. water	10	°C

AFTER preheating	in	Out
Consistency [%]	40	30
Total flow [kg/s]	15	19
Fiber flow [BDkg/s]	5,6	5,6
Water flow [kg/s]	9	9
Impr. Water flow [kg/s]	4	4
Energy chips [kW]	3330	3136
Energy impr water [kW]	919	1105
Total energy [kW]	4249	4241
Error [kW]	-8	
Temp in of impr. water	55	°C

(pinch temp: 57.5˚C, 2.5˚C less for water gives -> 55˚C)

The preheating heat demand for the impregnation water is calculated below.

Q [kW] = m×ΔT×Δcp = 4*(55*4.18)-(10*4.19) = 751 kW

When the impregnation water (10˚C) enters the impregnation tower it is mixed with the wood chips and water (70˚C), the mixture has a temperature of 57˚C. This mixture will enter the preheater at a temperature of 56˚C. When preheating the impregnation water to 55˚C the temperature of the mixture will be 67˚C and enter the preheater at a temperature of 66˚C.

Total temp out 57* °C

* about 56°C as specified in FlowMac (temp drop of about 1°C)

Total temp out **67*** °C

* will assume **66°C**, a temperature drop of 1°C

In the preheater the mixture is heated with steam to a temperature of 120˚C. The steam properties are shown in the table below.

Steam to the preheater:

Temp	134	C	
Pressure	3,2	bar(a)	
Flow	0,93	kg/s	
Enthalpy in	2728	kJ/kg	
Enthalpy cond.	561*	kJ/kg	**because other pressure inside of the preheater (3 bar(a)).*

The energy balance of the preheater before and after the preheating of the impregnation water is shown below. The condensate from the steam also gives some energy for the calculation of the energy out from the preheater.

Preheater:

BEFORE preheating	in	Out
Consistency [%]	50	46
Total flow (chips+water)[kg/s]	11,2	12,2
Fiber flow [BDkg/s]	5,6	5,6
Water flow [kg/s]	5,6	5,6
Steam water [kg/s]	0,93	0
Energy: chips + water [kW]	1 745	3 941
Energy: steam/cond. steam [kW]	**2 015**	472
Total energy [kW]	3 760 *	4 413 *
Error [kW]	653	

** should be the same if theoretical balance*

AFTER preheating

Temperature of chips+water when impregnation water is preheated:

66 °C

	in	out	
Energy chips [kW]	2 073	**3 941***	**constant*
Energy: steam/cond. Steam [kW]	**1 584**	370*	**iteration table next page*
Total energy	3 657	4 311	Δ 653*

**use same error as from “before”*

New steam flow [kg/s]:	**0,73**	=	1.584	MW
Reduced by:	**21%**	=	0.431	MW

By preheating the impregnation water from 10˚C to 55˚C the steam flow is reduced by 21% which correspond to a reduction of 0.43 MW of dirty steam.

As the steam demand in the preheater is unknown after the preheating of the impregnation water, the steam condensate is also unknown. The energy from the condensed steam after the preheating is calculated through iteration. A table of the iteration is shown below.

For the iteration:

Steam flow [kg/s]	**Energy: condensed steam [kW]**
0,93	472
0,9	457
0,85	432
0,8	406
0,75	381
0,74	376
0,73	371
0,72	366

Appendix 9 – The reboiler

The reboiler is a part of the steam recovery system of the TMP plant, where dirty steam generated from the refiners is converted into clean steam.

In every start-up of the TMP plant almost all steam is send to the scrubber. This is because the dirty steam at start up consists of a lot more chip rests and cannot be sent to the reboiler. At the same time the steam is entering the scrubber water is sprayed in. This is in order to make the heavy particles fall down, the dirty water is collected from the bottom of the scrubber. Half of the water is circulated as spraying water and half is sent to a press filtrate chest. The fibers in the water in the chest is later removed and added back to the pulp line. The high amount of fibers in the water makes this stream not suitable in heat exchangers. The spraying water entering the scrubber has a temperature of 62°C, which stays the same whether it is in start-ups or not.

The analysis of the plant presented in this thesis assumes a steady state condition. No start-ups were assumed and all dirty steam should be usable. But even at a steady state condition a lot of steam is sent to the scrubber. This is not because the steam is too dirty but due to the limited, maximal capacity of the reboiler.

In the simulated model (FlowMac) made by Norske Skog, no dirty steam was sent to the scrubber. However, the heater of stream number 37, white water continued, used dirty steam in the model but clean steam in reality. Therefore, in the analysis presented in this thesis, this dirty steam (4.3MW) is send to the scrubber.

The capacity tests of the reboiler was made one year ago and showed three test results of the capacity of the reboiler. The results were: 16.6, 16.8 and 17.3 MW. In our study the middle capacity was used, 16.8 MW.

Appendix 10 – Preheating opportunities and new reboiler

The preheating opportunities of dilution water to the refiners and the impregnation water gives an increased dirty steam production and decreased dirty steam consumption respectively. In order to preheat the streams there is a demand of heating that can be covered by heat exchanging with hot steams that need cooling, which will result in a reduced cooling demand. A summary of the effects of the preheating is shown in the table below.

Preheating opportunities	**Dilution water to the refiners [MW]**	**Impregnation water [MW]**	**Total [MW]**
Increased dirty steam production/ decreased dirty steam consumption	0.579	0.430	**1.009**
Heating demand for preheating	0.579	0.752	**1.331**
Reduced cooling demand	0.579	0.752	**1.331**

The unutilized dirty steam that currently is sent to the scrubber could be recovered as clean steam if the reboiler had a higher capacity. The total dirty steam that could be recovered as clean steam is shown in the table below.

Preheating opportunities and dirty steam unutilized	**Dirty steam [MW]**
From scrubber	4,273
From preheating dilution water to the refiners	0.579
From preheating impregnation water	0.430
Total dirty steam	**5,282**

With a new reboiler which has higher capacity than the existing one the dirty steam can be converted into clean steam. The efficiency of the existing reboiler is 87.9%, an efficiency taken from the simulated model (FlowMac) made by Norske Skog. The new reboiler was assumed to have the same efficiency as the existing one. The dirty steam from the scrubber, preheating of the dilution water to the refiners and the preheating of the impregnation water is converted into clean steam in the new reboiler; the clean steam production is shown in the table below.

Preheating opportunities and dirty steam unutilized	**Clean steam [MW]**
From scrubber	3.756
From preheating dilution water to the refiners	0.509
From preheating impregnation water	0.378
Total clean steam	**4.643**

However, this appendix only shows the opportunities with preheating. In Retrofit 4 there might not be enough heat available in streams to preheat the impregnation water and the dilution water to the refiners, therefore the total clean steam (4.6 MW) might not be reached in Retrofit 4 or in the combinations with Retrofit 4. This is shown in Appendix 12.

Appendix 11 – Heat pump

In section 5.6, the integration of a heat pump in a MER network is discussed. According to the GCC of the system, it is possible to achieve 2790 kW of steam savings if excess heat at 42 °C is lifted to 69 °C. This is the base for all the following calculations.

In the existing system, the white water (stream 37) demands 4273 kW at 69 °C, currently provided by steam. According to the data presented in Table 11(Chapter 4), the white water (stream 37) is heated from 56°C to 69°C, the stream has therefore a heat content of:

$$Q = F\,Cp\,\Delta T \Rightarrow F\,Cp = \frac{Q}{\Delta T} = \frac{4273\ kW}{(69-56)°C} = 225\ \frac{kW}{°C}$$

The heat pump should supply 2790 kW at 69 °C. Assuming a constant heat capacity, it is possible to calculate how much of the entire stream can be heated:

$$Q = F\,Cp\,\Delta T \Rightarrow F\,Cp = \frac{Q}{\Delta T} = \frac{2790\ kW}{(69-56)°C} = 214\ \frac{kW}{°C}; \qquad \left(65\%\ of\ 225\ \frac{kW}{°C}\right)$$

The heat needs to be supplied by a condensing refrigerant. If a ΔT_{min} of 10 degrees is selected, the chosen refrigerant needs to condensate at 79 °C and evaporate at 32 °C. For these preliminary calculations, n-butane was chosen as the working fluid due to its suitable working pressures within this interval of temperatures.

N-butane condenses at 79 °C at a pressure of approximately 990 kPa. The saturated vapour has a specific enthalpy of $690\ \frac{kJ}{kg}$ and the saturated liquid$390\ \frac{kJ}{kg}$. Assuming that saturated vapour enters the condenser and that there is no subcooling of the liquid, the flowrate of n-butane can be calculated:

$$Q = m\,\Delta h \Rightarrow m = \frac{Q}{\Delta h} = \frac{2790\ kW}{(690-390)\frac{kJ}{kg}} = 9.3\ \frac{kg}{s}$$

Assuming isenthalpic expansion in the valve, n-butane is expanded to a pressure of approximately 299 kPa where it evaporates at 32 °C. The enthalpy of the liquid-vapour mixture entering the evaporator is$390\ \frac{kJ}{kg}$. If there is no superheating of n-butane in the evaporator, the exit enthalpy of the saturated vapour is:$630\ \frac{kJ}{kg}$. The heat demand in the evaporator is consequently:

$$Q = m\,\Delta h = \left(9.3\ \frac{kg}{s}\right)(630-390)\frac{kJ}{kg} = 2234\ kW$$

In the existing system, the warm stream leaving TM2B (stream 15) is cooled from 61 °C to 32 °C Table 11 (Chapter 4) with a cold utility consumption of 4269 kW. The heat available in this stream in the temperature interval between 61 °C and 42 °C is 2802 kW. The specific heat content of this stream is therefore:

$$Q = F\,Cp\,\Delta T \Rightarrow F\,Cp = \frac{Q}{\Delta T} = \frac{2802\ kW}{(61-42)°C} = 147\ \frac{kW}{°C}$$

The heat pump demands 2234 kW at 42 °C. Assuming a constant heat capacity, it is possible to calculate how much of the entire stream needs to be used:

$$Q = F\,Cp\,\Delta T \Rightarrow F\,Cp = \frac{Q}{\Delta T} = \frac{2234\ kW}{(61-42)°C} = 117\ \frac{kW}{°C}; \qquad \left(80\%\ of\ 147\ \frac{kW}{°C}\right)$$

The compressor work can be calculated with and energy balance around the heat pump:

$$Q_{condensor} = Q_{evaporator} + W_{compressor}$$

$$W_{compressor} = Q_{condensor} - Q_{evaporator} = 558\ kW$$

Appendix 12 – Combinations of retrofit proposals

In section 5.7 the steam savings associated with combining different retrofits were presented.

In Retrofit 1 – light, Retrofit 2 – medium and Retrofit 3 – deluxe, steam savings are achieved by modifying the heat exchanger network and increasing internal heat recovery. The retrofitted heat exchanger networks cannot be implemented simultaneously. Each of these three retrofits is independent and makes use of almost the entire set of process streams. Retrofit 4 (preheating opportunities) and Retrofit 5 (heat pump) make use only of one or two streams and it is simpler to combine them with Retrofit 1-3.

Retrofit 4 – Preheating opportunities

Retrofit 4 requires a bigger reboiler and heat from an effluent stream. Retrofit 4 achieve energy savings in three different ways: recovering dirty steam currently sent to the scrubber, preheating dilution water and preheating impregnation water.

In the existing network the other effluent from TM2B (stream 17) is sent to the effluent treatment plant. This stream has 1275 kW of heat available at a temperature of 32°C→70°C that can be used for preheating streams. Of the heat available, 525 kW can be used to preheat the dilution water to the refiners and 750 kW to preheat the impregnation water. According to the calculations presented in Appendix 7 and considering a reboiler efficiency of 87.9%, preheating of the dilution water to the refiners with 525 kW leads to 525 kW of dirty steam and 462 kW of clean steam. According to the calculations presented in Appendix 8, the preheating of the impregnation water with 750 kW leads to 430 kW of dirty steam savings and 378 kW of clean steam. The clean steam savings achieved are presented in Table 39.

Table 39 Preheating opportunities, existing network

	Heating demand [kW]	Dirty steam [kW]	Clean steam [kW]
Dilution water to the refiners	525	525	462
Impregnation water	750	430	378
Dirty steam to the scrubber	-	4273	3756
			4596

In Retrofits 1-3, the other effluent from TM2B (stream 17) is used to heat the warm water (stream 32) and therefore less heat is available for the preheating. Of the 986 kW left, 236 kW can be used to preheat the dilution water to the refiners and 750 kW to preheat the impregnation water. The results are presented in Table 40.

Table 40 Preheating opportunities, Retrofits 1-3

	Heating demand [kW]	Dirty steam [kW]	Clean steam [kW]
Dilution water to the refiners	236	236	207
Impregnation water	750	430	378
Dirty steam to the scrubber	-	4273	3756
			4341

Retrofit 5 – Heat Pump

Retrofit 5 requires a heat source at a temperature about 42 °C or warmer and a heat sink at a temperature lower than 69 °C. Streams that satisfy these requirements are: the warm stream leaving TM2B (stream 15) as a heat source and the white water (stream 37) as a heat sink. Additionally, it demands compressor work depending on the size of the heat pump.

In the existing network as well as in Retrofit 1, the warm stream leaving TM2B (stream 15) is sent to the effluent treatment plant. This stream has 2802 kW of heat available at a temperature of 42°C→61°C that can be used for the heat pump.

According to the calculations presented in Appendix 11 and assuming a constant COP=5, the heat delivered by a heat pump with Q_{evap}=2805 kW is: Q_{cond}=3503 kW. The results are presented in Table 41.

Table 41 Heat pump integration, existing network and Retrofit 1

	Q_{evap} [kW]	W_{comp} [kW]	Q_{cond} [kW]
Existing network and Retrofit 1	2802	701	3503

In Retrofit 2 the warm stream leaving TM2B (stream 15) is used to heat the air for mix (streams 24-27) and has less heat available for heat pumping. The stream has however 869 kW available and a smaller heat pump can be integrated. The results are presented in Table 42.

Table 42 Heat pump integration, Retrofit 2

	Q_{evap} [kW]	W_{comp} [kW]	Q_{cond} [kW]
Retrofit 2	869	217	1086

In Retrofit 3, even less heat is available for heat pumping as the warm stream leaving TM2B (stream 15) is used to heat the air for mix (streams 24-27) and the air to the dryer (streams 20-23). In this case only 129 kW can be used in a heat pump. The results are presented in Table 43.

Table 43 Heat pump integration, Retrofit 3

	Q_{evap} [kW]	W_{comp} [kW]	Q_{cond} [kW]
Retrofit 3	129	32	162

Combination of retrofits

The heat recovered by Retrofit 4 and Retrofit 5 is presented in Table 44 for the different retrofit combinations.

Table 44 Heat recovered Retrofit 4 and Retrofit 5

	Heat recovered [kW]		
Heat exchanger network configuration	**Retrofit 4 - Preheating opportunities**	**Retrofit 5 - Heat pump**	**Retrofit 4+ Retrofit 5**
Existing network	4 595	3 503	4 595+3 503=8 098
Retrofit 1	4 341	3 503	4 341+3503=7 844
Retrofit 2	4 341	1 086	4 341+1 086=5 427
Retrofit 3	4 341	162	4 341+162=4 503

The total heat recovered in every retrofit combination is presented in Table 45 .

Table 45 Total heat recovered, combination retrofits

		Total heat recovered [kW]		
Heat exchanger network configuration	**Retrofitting HX-network alone**	**Retrofit 4 - Preheating opportunities**	**Retrofit 5 - Heat pump**	**Retrofit 4+ Retrofit 5**
Existing network	0	0+4 595=4 595	0+3 503=3 503	0+8 098=8 098
Retrofit 1	1 082	1 082+4 341=5 424	1 082+3 503=4 585	1 082+7 844=8 926
Retrofit 2	2 222	2 222+4 341=6 564	2 222+1 086=3 308	2 222+5 427=7 650
Retrofit 3	2 867	2 867+4 341=7 209	2 867+162=3 029	2 867+4 503=7 370

Appendix 13 – Calculations of the future scenarios

The calculations for the future scenarios are presented in this appendix.

Recycled paper and filler

The changes in the first scenario are:

- 30 % less TMP production → 30 % less steam (both dirty and clean) production in the TMP plant
- As less TMP is produced the bark supply to the boiler house will be reduced (reduced clean steam production)
- As some DIP is used, the DIP sludge from the DIP plant will be increased and burnt in the boiler house (increased clean steam production)

1) In order to calculate the changed steam production in the boiler house some basic calculations, concerning the bark and DIP sludge, must first be done.

<u>How much bark is produced for every kilogram of TMP?</u>

Assuming that 2% of the wood is lost during debarking, chipping and refining and that the amount of bark in wood is 8.93% (from simulation model FlowMac made by Norske Skog):

$$x\,kg\ TMP\left(\frac{kg\ wood}{0.98\,kg\ TMP}\right)\left(\frac{0.0893\,kg\ bark}{kg\ wood}\right)[=]kg\ bark$$

<u>What is the effective heating value of bark?</u>

The heating value of spruce bark is 8000 BTU/lb [16].

$$8000\frac{BTU}{lb}\left(\frac{1055\,J}{1\,BTU}\right)\left(\frac{1\,lb}{0.4536\,kg}\right)=1.86\times10^{7}\frac{J}{kg\ bark}$$

<u>How much steam can be produced?</u>

- Enthalpy of vaporization:

$$\begin{array}{lll} & \left\{\begin{array}{l}103\text{ C}\\ 2.1\text{ bar}\end{array}\right. \rightarrow & \left\{\begin{array}{l}134\text{ C}\\ 3.2\text{ bar}\end{array}\right. \\ & 433.6\text{ kJ/kg} & 2728\text{ kJ/kg} \\ \rightarrow & 2728-433.6\ = & 2294.4\text{ kJ/kg}\end{array}$$

$$1\ kg\ TMP\left(\frac{kg\ wood}{0.98\ kg\ TMP}\right)\left(\frac{0.0893\ kg\ bark}{kg\ wood}\right)\left(\frac{1.86\times 10^{7}\ J}{kg\ bark}\right)\left(\frac{kg\ steam}{2294.83\times 10^{3}\ J}\right)$$
$$= 0.74\ kg\ steam$$

Using more DIP more DIP sludge is produced, the DIP sludge is burnt in the boiler house.

How much DIP sludge is produce for every kg of DIP?

According to FlowMac the flowrate of DIP is 47 kg/s (9% consistency) and the flowrate of DIP sludge is 1.2 kg/s, of which:

0.4 kg/s fiber

0.3 kg/s filler

0.5 kg/s water

1.2 kg/s DIP-sludge

Assuming that the heating value of the fibers is the same as wood i.e. $18.5-21\ \frac{MJ}{kg}$, the steam produced for every kilogram of DIP is:

$$1\ kg\ DIP\left(\frac{1.2\ kg/s\ DIP\ sludge}{(47)(0.09)\ kg/s\ DIP}\right)\left(\frac{0.4\ kg/s\ fiber}{1.2\ kg/s\ DIP\ sludge}\right)\left(\frac{19\times 10^{6}\ J}{kg\ fiber}\right)\left(\frac{kg\ steam}{2294.83\times 10^{3}\ J}\right)$$
$$= 0.07\ kg\ steam$$

2) The reduction of steam production from the decreased TMP production is presented below.

Clean steam production before scenarios: 16.8 MW

Dirty steam production before scenarios: 6.84 MW

The change of steam production when the production of TMP is reduced:

30% less TMP gives a new clean steam production of: 0.7×16.8 = 11.76 MW

30% less TMP gives a new dirty steam production of: 0.7×6.84= 4.79 MW

The steam production in the boilers is affected by the change in composition furnish:

The production of TMP is 5.5 BDkg/s, this number is used in the calculations below.

- The bark is decreased because of less TMP production, this gives a less steam production;

Steam produced from bark before: **0.74**×5.5= 4.07 kg/s → **8.783** MW*

Steam produced from bark after: 4.07×0.7= 2.849 kg/s → **6.148** MW*

Deficit **1.221 kg/s**

- The DIP is increased because of less TMP production, this gives a less steam production;

Steam produced from DIP sludge before: 0 kg/s → **0** MW

Steam produced from DIP sludge after: 0.2*5.5***0.07**= **0.077** kg/s → **0.166** MW*

Surplus **0.077 kg/s**

*(2728kJ/kg-570kJ/kg) × mass flow [kg/s] = load [kW]

3) The results are shown in the table below.

After the reduction of TMP production the clean steam production is reduced but as the reboiler is running with a smaller load some dirty steam, 2.63 MW, can be converted into clean steam and the reduction of clean steam production is thus less.

Scenario with recycled paper (DIP) and filler	Clean steam TM2B	Steam from bark	Steam from DIP sludge
Steam production in existing system [MW]	16.80	8.78	0.00
Steam production in scenario with DIP and filler introduced [MW]	11.76+2.63=14.39	6.15	0.17
Total reduction/increase [MW]	**-2.41**	**-2.63**	+**0.17**

Total reduction of steam production: -2.41 + (-2.63) + 0.17= -4.87 MW

4) The reduction of dirty steam is presented in the table below.

The additional dirty steam which is used in the reboiler is subtracted from the production, 2.99 MW, this is converted, in the reboiler (efficiency of 87.9 %), into 2.63 MW of clean steam.

Scenario with recycled paper (DIP) and filler	Dirty steam TM2B
Dirty steam production in existing system [MW]	6.84
Dirty steam production in scenario with DIP and filler [MW]	4.79-2.99=1.8
Reduction [MW]	**-5.04**

5) The calculations of the total reduction of clean steam production and dirty steam production in the scenario with DIP and filler introduced are shown in the table below.

Steam production	*Existing system*	*Scenario with DIP and filler introduced*	*Change*
Dirty steam [MW]	**6.8**	**1.8**	1.8-6.8= **-5**
Clean steam [MW]	(**16.8**) 16.8+8.78=**25.6**	(**14.4**) 14.4+6.15+0.17=**20.72**	(14.4-16.8 = **-2.4**) 20.72-25.6= **-4.88**

6) The calculations of the reduction in steam consumption in the scenario with DIP and filler introduced are shown in the table below.

	Existing system	*Scenario with DIP and filler introduced*	*Change*
Dirty steam demand			
Steaming [MW]	0.6	0.7×0.6= 0.4	0.4-0.6= -0.2
Preheating [MW]	2.0	0.7×2.0= 1.4	1.4-2.0= -0.6
Total [MW]	**2.6**	**1.8**	**1.8-2.6= -0.8**
Clean steam demand			
Stream 37 [MW]	4.3	0.7×4.3= 3.0	3.0-4.3= -1.3
Total [MW]	**4.3**	**3.0**	**3.0-4.3= -1.3**

7) The comparison between the reduction of clean steam production and the reduction of clean steam demand from the retrofits are in the report presented with a table.

In the table the reduction of clean steam production is subtracted with the reduction of clean steam demand achieved from the retrofits. The data for the retrofits, in the diagram, are presented in Table 25 in section 5.7. The data for the steam reduction in the scenario with DIP and filler introduced are calculated in this appendix; see point 3).

The table, Table 28 in section 6.1, presented in the report is an illustration of whether the reduction of steam demand is enough to cover the reduction in steam production in the scenario with DIP and filler introduced. The table is calculated as shown in the table below.

Heat exchanger network configuration	**Solving pinch violations in heat exchanger network**	**Retrofit 4 - Preheating opportunities**	**Retrofit 5 – Heat pump**	**Retrofit 4+ Retrofit 5**
Surplus/deficit steam in existing system [MW]	0-4.9= **-4.9**	0.839-4.9= **-4.0**	3.503-4.9= **-1.4**	4.342-4.9= **-0.5**
Surplus/deficit steam in Retrofit 1 [MW]	1.082-4.9= **-3.8**	1.667-4.9= **-3.2**	4.585-4.9= **-0.3**	5.170-4.9= **0.3**
Surplus/deficit steam in Retrofit 2 [MW]	2.222-4.9= **-2.7**	2.807-4.9= **-2.1**	3.308-4.9= **-1.6**	3.893-4.9= **-1.0**
Surplus/deficit steam in Retrofit 3 [MW]	2.868-4.9= **-2.0**	3.452-4.9= **-1.4**	2.029-4.9= **-1.9**	3.614-4.9= **-1.3**

More energy efficient refining

The scenario with more energy efficient refining the first scenario with recycled paper and filler is already included. The only change of the steam production is caused by the more energy efficient refining. Two measures of increasing the energy efficiency of the refining are:

- Mechanical pre-treatment of the chips, gives a reduction of 5 % of the electricity consumption of the refining.
- The mechanical pre-treatment together with higher refining intensity (double disc refiners/higher rotational speed on the existing ones) gives a reduction of 20 % of electricity consumption of the refining (without the mechanical pre-treatment of the chips the reduction would be 15 %)

The reduction of electricity consumptions are assumed to cause the same reduction of generated steam from the refiners. The reduction of steam is presented the table below. In this scenario also some dirty steam, 2.43 MW or 1.82 MW, can be converted into clean steam in the reboiler as the reboiler is running with a smaller load.

Scenario with DIP and filler introduced and more energy efficient refining	Clean steam TM2B	Steam from bark	Steam from DIP sludge
Steam production in existing system [MW]	16.8	8.78	0.0
Steam production after introduction of DIP and filler and mech. pre-treatment of chips [MW]	(11.76*0.95)+2.42=13.59	6.15	0.17
Total reduction/increase [MW]	**-3.21**	**-2.63**	**+0.17**
Steam production after introduction of DIP and filler and mech. pre-treatment of chips and higher refining intensity [MW]	(11.76*0.85*0.95)+1.82=11.32	6.15	0.17
Total reduction [MW]	**-5.5**	**-2.63**	**+0.17**

Compared to the steam production before the scenarios (steam production in the existing system) the total reduction is **-3.21-2.63+0.17= -6 MW** for DIP and filler introduced together with only mechanical pre-treatment and **-5.5-2.63+0.17= -8.0 MW** for DIP and filler introduced together with mechanical pre-treatment and higher refining intensity.

The production of dirty steam is also reduced, see table below. The additional dirty steam which is used in the reboiler is subtracted from the production, 2.75 MW and 2.06 MW, this is converted in the reboiler (efficiency of 87.9 %) to the amount of 2.42 MW and 1.82 MW of clean steam.

Scenario with more energy efficient refining	Dirty steam TM2B
Steam production in existing system [MW]	6.84
Dirty steam production after introduction of DIP and filler and mech. pre-treatment of chips [MW]	(4.79*0.95)-2.75= 1.8
Dirty steam production after introduction of DIP and filler and mech. pre-treatment of chips and higher refining intensity [MW]	(4.79*0.85*0.95)-2.06= 1.8

In section 6.2 a summary of the reduction of clean steam production and dirty steam production is presented in Table 30. The calculations of the table are presented in the same table below.

Steam production	***Existing system***	***Scenario with DIP & filler introduced & mechanical pre-treatment of chips***	***Change***	***Scenario with DIP & filler introduced & mechanical pre-treatment of the chips & higher refining intensity***
Dirty steam [MW]	**6.8**	**1.8**	1.8-6.8= **-5**	**1.8**
Clean steam [MW]	(**16.8**) **25.6**	(**13.59**) 13.59+6.15+0.17= **19.9**	(13.59-16.80= **-3.2**) 19.9-25.6= **-5.7**	(**11.3**) 11.3+6.15+0.17=**17.6**

The comparison between the reduction of clean steam production and the reduction of clean steam demand from the retrofits are in the report presented with a table.

In the table the reduction of clean steam production is subtracted with the reduction of clean steam demand achieved from the retrofits. The data for the retrofits, in the diagram, are presented in Table 25 in section 5.7. The data for the steam production reduction in the scenario with DIP and filler introduced together with mechanical pre-treatment without or with higher refining intensity are calculated in this appendix; see above.

The table, Table 30 in section 6.2, presented in the report is an illustration of whether the reduction of steam demand is enough to cover the reduction in steam production in the scenario with DIP and filler introduced and more energy efficient refining. The table is calculated as shown in the following table (the calculation in the first row is without higher refining intensity and in the second row with higher refining intensity).

Heat exchanger network configuration	**Solving pinch violations in heat exchanger network**	**Retrofit 4 - Preheating opportunities**	**Retrofit 5 – Heat pump**	**Retrofit 4+ Retrofit 5**
Surplus/deficit steam in existing system [MW]	0-5.7= **-5.7**| 0-8= **-8.0**	4.643-5.7= **-4.8**| 4.643-8= **-7.1**	2.790-5.7= **-2.2**| 2.790-8= **-4.5**	7.433-5.7= **-1.3**| 7.433-8= **-3.6**
Surplus/deficit steam in Retrofit 1 [MW]	1.082-5.7= **-4.6**| 1.082-8= **-6.9**	5.725-5.7= **-4.0**| 5.725-8= **-6.3**	3.872-5.7= **-1.1**| 3.872-8= **-3.4**	8.137-5.7= **-0.5**| 8.137-8= **-2.8**
Surplus/deficit steam in Retrofit 2 [MW]	2.222-5.7= **-3.5**| 2.222-8= **-5.7**	6.865-5.7= **-2.9**| 6.865-8= **-5.1**	2.222-5.7= **-2.4**| 2.222-8= **-4.6**	6.865-5.7= **-1.8**| 6.865-8= **-4.1**
Surplus/deficit steam in Retrofit 3 [MW]	2.867-5.7= **-2.8**| 2.867-8= **-5.1**	7.510-5.7= **-2.2**| 7.510-8= **-4.5**	2.867-5.7= **-2.7**| 2.867-8= **-4.9**	7.510-5.7= **-2.1**| 7.510-8= **-4.3**

Appendix 14 – Calculations of the comparison of the results with a similar study of a TMP model mill

The calculations for every graph of the comparison of the results from a similar study of a TMP model mill are presented in this appendix.

Calculations for: Figure 33

The results from the process integration of the model mill:

The model mill	**Before PI**	**After PI**
Steam surplus [MW]	21.5	30.3
Cooling demand [MW]	26.8	13.6

The increased steam demand and the decreased cooling demand of the model mill after the process integration is calculated:

Increase of steam surplus = 30.3/21.5 = 1.377 → 41 %

Decrease of cooling demand = 1- (13.6/26.8) = 0.46 → 49 %

Calculations for: Figure 34 and Figure 35

The figures for this diagram are based on the reduction of heating demand from the different retrofits and combinations between them. The table below presents the reduction of heating demand (steam demand) this table is also presented in Table 25 in section 5.7.

Total heat recovered [MW]

Heat exchanger network configuration	**Solving pinch in heat exchanger network**	**Retrofit 4 - Preheating opportunities**	**Retrofit 5 - Heat pump**	**Retrofit 4+ Retrofit 5**
Existing network	0.0	4.6	3.5	8.1
Retrofit 1	1.1	5.4	4.6	8.9
Retrofit 2	2.2	6.6	3.3	7.6
Retrofit 3	2.9	7.2	3.0	7.4

For the reduction of the cooling demand, this is calculated in the table below.

Heat exchanger network configuration	**Solving pinch in heat exchanger network**	**Retrofit 4 - Preheating opportunities**	**Retrofit 5 - Heat pump**	**Retrofit 4+ Retrofit 5**
Existing network [MW]	0.0	0.525+0.750=1.3[37]	2.8[38]	1.3+2.8=4.1
Retrofit 1 [MW]	1.1	1.1+0.236+0.750=2.1	1.1+2.8=3.9	2.1+2.8=4.9
Retrofit 2 [MW]	2.2	2.2+0.236+0.750=3.2	2.2+0.869=3.1	3.1+0.236+0.750=4.1
Retrofit 3 [MW]	2.9	2.9+0.236+0.750=3.9	2.9+0.129=3.0	3.9+0.129=4.0

From the two last tables the reduction of steam demand can be compared to the current clean steam demand, 26.1 MW, and the reduction of cooling demand can be compared to the current cooling demand, 17.9 MW. As savings of dirty steam not directly correspond to a reduction of heating demand, as there is already a surplus of dirty steam, the reduction of heating demand refers to the reduction of only clean steam usage.

The first table present the reduction of heating and cooling demand achieved in the model mill through process integration. The later tables present the reduction achieved in the real mill. The reduction is shown in percentages.

Model mill - reduction of heating and cooling demand:

The reduction of heating and cooling demand	Model mill
Heating demand	1-(55.7/64.5)= 14 %
Cooling demand	1-(14.5/26.8)= 49 %

Real mill – reduction of heating demand:

Reduction of heating demand	**Solving pinch in heat exchanger network**	**Retrofit 4 - Preheating opportunities**	**Retrofit 5 - Heat pump**	**Retrofit 4+ Retrofit 5**
Existing network	0	4.6/26.1= 18%	3.5/26.1= 13%	8.1/26.1= 31%
Retrofit 1	1.1/26.1= 4%	5.4/26.1= 21%	4.6/26.1= 18%	8.9/26.1= 34%
Retrofit 2	2.2/26.1= 8%	6.6/26.1= 25%	3.3/26.1= 13%	7.6/26.1= 29%
Retrofit 3	2.9/26.1= 11%	7.2/26.1= 28%	3.0/26.1= 12%	7.4/26.1= 28%

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[37] Total cooling demand from the preheating opportunities, see Appendix 10 and Appendix 12.

[38] The cooling due to the heat pump integration, the same as Q_{evap}, see Appendix 12.

Real mill – reduction of cooling demand:

Reduction of cooling demand	**Solving pinch in heat exchanger network**	**Retrofit 4 - Preheating opportunities**	**Retrofit 5 - Heat pump**	**Retrofit 4+ Retrofit 5**
Existing network	0	1.3/17.9= 7%	2.8/17.9= 16%	4.1/17.9= 23%
Retrofit 1	1.1/17.9= 6%	2.1/17.9= 12%	3.9/17.9= 22%	4.9/17.9= 27%
Retrofit 2	2.2/17.9= 12%	3.2/17.9= 18%	3.1/17.9= 17%	4.1/17.9= 23%
Retrofit 3	2.9/17.9= 16%	3.9/17.9= 22%	3.0/17.9= 17%	4.0/17.9= 22%

Model mill has a surplus of steam (21.5 MW). The surplus increases by 41 % after the process integration. For the real mill, there is no steam surplus but a deficit of 9.3 MW. By process integration this deficit can be reduced as the system will have a reduced steam demand. The reduction of this deficit will be different in the different retrofits and combinations of retrofits. The new steam demand, steam deficit and the reduction of the steam deficit are calculated for the different retrofits and combinations of retrofits in following table.

Real mill	**Reduction of steam demand [MW]**	**Steam deficit [MW]**	**Reduction of steam deficit [%]**
Before PI	**0**	**9.3**	**0**
Existing system + Retrofit 4	4.6	9.3-4.6= **4.7**	4.6/9.3= **49%**
Existing system + Retrofit 5	3.5	9.3-3.5= **5.8**	3.5/9.3= **38%**
Existing system + Retrofit 4 + Retrofit 5	8.1	9.3-8.1= **1.2**	8.1/9.3= **87%**
Retrofit 1	1.1	9.3-1.1= **8.2**	1.1/9.3=**12%**
Retrofit 1 + Retrofit 4	5.4	9.3-5.4= **3.9**	5.4/9.3=**58%**
Retrofit 1 + Retrofit 5	4.6	9.3-4.6= **4.7**	4.6/9.3=**49%**
Retrofit 1 + Retrofit 4 + Retrofit 5	8.9	9.3-8.9= **0.4**	8.9/9.3=**96%**
Retrofit 2	2.2	9.3-2.2= **7.1**	2.2/9.3=**24%**
Retrofit 2 + Retrofit 4	6.5	9.3-6.5= **2.8**	6.5/9.3=**69%**
Retrofit 2 + Retrofit 5	3.3	9.3-3.3= **6**	3.3/9.3=**35%**
Retrofit 2 + Retrofit 4 + Retrofit 4	7.6	9.3-7.6= **1.7**	7.6/9.3=**82%**
Retrofit 3	2.9	9.3-2.9= **6.5**	2.9/9.3=**31%**
Retrofit 3 + Retrofit 4	7.2	9.3-7.2= **2.1**	7.2/9.3=**77%**
Retrofit 3 + Retrofit 5	3.0	9.3-3.0= **6.3**	3.0/9.3=**32%**
Retrofit 3 + Retrofit 4 + Retrofit 5	7.4	9.3-7.4= **1.9**	7.4/9.3=**79%**