Energy and Water Savings in a Pulp and Paper Mill

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February 2004

Declaration

No portion of the work referred to in this dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institution of learning.

Sónia Cristina Nobre Monteiro

Manchester, February 2004

Acknowledgements

I would like to thank my supervisor Dr Jiri Klemes for his guidance, recommendations, assistance and support throughout this dissertation.
I also would like to express my gratitude to my co-supervisor Simon Perry for his recommendation and assistance.

I extend my thanks to Eng. Alexandre Martins and Dr Paulo Barata from PORTUCEL for their useful assistance and data supplied.

I would like say thank you to my family, especially to my parents (Carlos Monteiro and Palmira Monteiro) and to my brother for their love, understanding, moral support and for not letting me give up when I intended to do so. Thank you also to my grandmother for her encouragement.

For the support and friendship in this academic year, I would like to express my appreciation to all my classmates.

Last but not least, my thanks to all my friends and flatmates for their encouragement and support.

Sónia Cristina Nobre Monteiro

Manchester, February 2004

Abstract

The reduction of energy consumption in a technical and economically efficient way has become a very important issue in the pulp and paper industry. New environmental limitations are increasing the necessity of a reduction of water consumption and in steam savings. Closure of the water circulation can reduce water requirements but it also imposes a creation of new treatment processes to remove undesirable elements. The possibility of creating a power market, gives new opportunities for electric power cogeneration in this type of industry.

The objective of this work is the evaluation of energy used in the mill, to identify the potential for energy savings: and, consequently, the environmental impact and structural modification of the process. The Pinch technology was used as a tool for the identification of potential savings in energy. The determination of the economic feasibility of energy savings arises as a consequence. The cost analysis for this type of investment is fundamental for the pulp and paper industry.

The results show that there is an excess of heat usage in the pulp drying stage. This excess of heat can be used at other stage in the pulp mill with different savings.

Table of Contents

DECLARATION **1**

ACKNOWLEDGEMENTS **2**

ABSTRACT **3**

LIST OF FIGURES **6**

LIST OF TABLES **7**

NOMENCLATURE **8**

1. INTRODUCTION 11
   - *1.1. Objectives 13*
2. PROCESS DESCRIPTION 14
   - *2.1. Fibre Line 15*
   - *2.2. Chemical Recovery 22*
   - *2.3. Chemical Products 31*
   - *2.4. Energy Production 33*
   - *2.5. Wastewater Treatment 35*
3. PROCESS ANALYSIS 36
   - *3.1. Drying Process Analysis 38*
   - *3.2. Overall Analysis 36*
4. LITERATURE REVIEW 40
   - *4.1. Heat Exchanger Network 41*
   - *4.2. Capital, Energy Trade-offs 43*
   - *4.3. Retrofit 45*
   - *4.4. Methodologies used in the Pulp and Paper Industry 48*
   - *4.5. Critical Evaluation 51*
5. METHODOLOGY 53
   - *5.1. Data Extraction 55*
   - *5.2. Economic Data 60*
6. RESULTS 61

6.1. Existing Process ... 61
6.2. Retrofit ... 64
6.3. Network Pinch method ... 75
6.4. Proposed Modifications Evaluation ... 76
6.5. Summary of the results ... 80
7. DISCUSSION ... 82
8. CONCLUSION ... 84
9. SUGGESTIONS FOR FURTHER WORK ... 86

REFERENCES ... 87

APPENDICES ... 92

List of Figures

Figure 2.1 - Global Kraft Process. (Martins & Barata, 2003) 14
Figure 2.2- Summary of the different stages at the Fibre line. 15
Figure 2.3- Wood-handling process. (Martins & Barata, 2003) 16
Figure 2.4- Diagram of a pulp *Fourdrinier* wet end forming table. 20
Figure 2.5- Schematic representation of the press process (Biermann, 1996, p 236). 21
Figure 2.6- Diagram for chemical recovery. 23
Figure 2.7- Long tube vertical (LTV) rising evaporator (Biermann, 1996, pp 105). 25
Figure 2.8- Schematic figure of a Falling-film plate-type effect (Martins & Barata, 2003). 26
Figure 2.9- Diagram of the chemicals production with SVP-Lite process. 32
Figure 2.10- Energy and steam consumption and production. 34
Figure 3.1- Drying Machine (Martins & Barata, 2003). 39
Figure 4.1- The process design 'onion diagram' 40
Figure 4.2 - Grid diagram of a process with one heat exchanger and one hot utility. 42
Figure 4.3 - Plot of surface area against energy. 45
Figure 5.1- Methodology steps. 54
Figure 5.2- Heat exchanger present in the drying process (Martins & Barata, 2003). 55
Figure 5.3- *Devron* presented in the drying process (Martins & Barata, 2003).. 55
Figure 5.4- Dryer second and third group of cylinders. 56
Figure 5.5- Heat exchangers (pre-heaters) representation. 58
Figure 6.1- Composite Curves for the existing process. 61
Figure 6.2- Existing heat exchanger network. 63
Figure 6.3- Energy-area plot for the drying process. 65
Figure 6.4- Capital investment (€) against energy savings (€/y). 68

FIGURE 6.5- SCHEMATIC REPRESENTATION OF THE CROSS-PINCH HEAT EXCHANGERS....... 70
FIGURE 6.6- HEAT EXCHANGER NETWORK AFTER RECONNECTION. 72
FIGURE 6.7- RETROFIT DESIGN REPORT (SPRINT, 2003)... 73
FIGURE 6.8- BOILER FEED WATER TANK WITH THE PROPOSE MODIFICATION...................... 76
FIGURE 6.9- HEAT EXCHANGER NETWORK FOR CASE 2. 78

List of Tables

TABLE 2.1- STEAM PRODUCED AND USED WITH RESPECT TO ABSOLUTE PRESSURE IN (KPA). 33
TABLE 5.1- ENERGY CONSUMPTION FOR EACH STAGE IN THE PRODUCTION OF PULP.......... 53
TABLE 5.2- STREAMS EXTRACTED FROM THE FLOW SHEET. 56
TABLE 5.3 - EXISTING STREAMS IN THE FLOW SHEET. 59
TABLE 5.4- UTILITY COSTS IN EUROS AND POUNDS... 60
TABLE 6.1 - HEAT EXCHANGERS PROFILE. 62
TABLE 6.2- AVERAGE SHELL AREA FOR DIFFERENT RANGES OF HEAT EXCHANGERS SIZES. 67
TABLE 6.3- CAPITAL INVESTMENT AND ENERGY SAVINGS CORRESPONDING TO DIFFERENT PAYBACKS... 69
TABLE 6.4- HEAT EXCHANGER CONDITIONS. 77
TABLE 6.5- RESUME OF THE RESULTS OBTAINED. 80
TABLE 6.6- RESULTS SUMMARY FOR CAPITAL INVESTMENT (€) AND ANNUAL SAVINGS (€/Y). 81

Nomenclature

AD	Air dried.
AS	Secondary air.
AP	Primary air.
A_{TOT}	Network total area (m^2).
CC	Continuous cooking.
CLR	Causticizing and lime reburning.
CP	Heat capacity flow rate (kW/ºC).
CPH	Combine power and heat.
CU	Cold utility.
DM	Drying machine.
ESP	Electrostatic precipitator.
Evap. II	Evaporation II.
Evap. III	Evaporation III.
HEN	Heat exchanger network.
h_k	Individual stream loads ‘film and fouling’ coefficients (kW/m^2°C).
HPS	High pressure steam produced in the bark boiler and recovery boiler with a pressure of 6101 kPa.
HTC	Heat transfer coefficient (kW/m^2°C).
HU	Hot utility.
LBH	Heavy black liquor.
LBI	Intermediate black liquor.
LPS II	Low pressure steam produced in turbine III, with a pressure of 461 kPa.
LPS I	Intermediate low pressure steam used in the dying machine III, with a pressure of 601 kPa.
LW	White liquor.
LWH	Heavy white liquor.
LWW	Weak white liquor.

MEE	Multiple effect evaporation
MER	Maximum Exchanger Recovery.
MPS	Medium pressure steam produced from the HPS in turbine III, with a pressure of 1050 kPa.
NCG	Non condensable gases.
N_{units} or U_{units}	Minimum number of units or matches.
Q_{Cmin}	Minimum cold utility required (kW).
Q_{Hmin}	Minimum hot utility required (kW).
Q_j	Section j stream population k.
q_k	Individual stream heat loads (kW).
RB	Recovery boiler.
S or N	Number of streams including utilities.
SVP	Process used to produce Chlorine dioxide from methanol, sodium chlorate and sulphuric acid.
Ts	Supply temperature (ºC).
Tt	Target temperature (ºC).
U	Overall heat transfer coefficient ($kW/m^{2o}C$).
WC45	Warm water (40 ºC).
WC75	Hot water (83 ºC).
α	Area efficiency.
ΔA	Additional area required (m^2).
ΔH	Enthalpy Variation (kW).
ΔN	Ration between the ΔA and average size of exchanger's shell.
ΔT	Temperature difference (ºC).
ΔT_{LMk}	Log mean temperature difference for the interval k (ºC).
ΔT_{min}	Minimum temperature difference (ºC).

Subscripts

bp	Bleached pulp.
bs	Brown stock.
min	Minimum.

Superscripts

- (Over bar)	Average value.

1. Introduction

One of the biggest problems in modern times is the environmental situation. Emissions are the main cause of the greenhouse effect and its reduction is a scope to achieve. On the other hand water is a precious belonging, which has been used and wasted, in large quantities by industry. The reduction and treatment of water is very important to avoid pollution of the seas, rivers and lakes in the world. The reduction of emissions like CO_2 may be achieved with the use of biomass as a fuel instead of fossil fuels. Closed water circulation may be the solution to the excess of water used.

The reduction of energy and water, taking in to account the environmental impact, is one of the scopes of the pulp and paper industry. It is also an aim of PORTUCEL as an industry of pulp and paper. The reduction of energy used causes a surplus of biomass or a surplus of energy produced. In the case of PORTUCEL, where the production of pulp and paper are separated, the surplus in terms of energy can be imported to the paper production. In the case of biomass it may be possible to use it to replace the fossil fuel already used.

PORTUCEL belongs to the PORTUCEL-SOPORCEL group, which is one of the five largest European producers of uncoated wood free paper. PORTUCEL is one of the most important in Europe. Its production is 480 000 ADt/year of eucalyptus bleached pulp in the kraft process. The consumption of water and energy is respectively 45 m^3/ADt (cubic meter per air-dried metric tonne) and 9.35 t/ADt (tonne per air-dried metric tonne). This consumption of water when compared with pulp mills already process integrated is higher. In modern mills, like in the Scandinavian industry, water consumption decreases to 5-10 m^3/ADt (Edelmann, 1999).

The increase in environmental restrictions is closely related with changes in the technical and economical field of the pulp and paper industry. These restrictions may increase the opportunities for energy and water savings. A cost-efficient reduction may also lead to new investments.

The storage of warm and hot water is normal in pulp and paper mills. The surplus of energy spent to heat up the water can be available for use in another part of the plant, for example in the drying or evaporation process. These processes are the most energy consuming in the PORTUCEL pulp mill. The condensed steam is used as a heat source. The condensate is used as boiler feed water; using this source the reduction of water usage on it is possible.

The pulp drying part is one of the most energy consuming processes. It consumes approximately 29 % of the global energy consumed. A substantial reduction in the energy consumed in this process will lead to a reduction in the overall energy consumed. This also means savings in biomass and black liquor. From another point of view, the surplus of energy can be used in another part of the mill or can be exported to the paper mill. The evaporation part was also mentioned in the paragraph above. Its energy consumption is close to 38 % of the global energy produced and is greater than the energy consumed in the drying part; however the evaporation process, in PORTUCEL, cannot be redesign.

The problem of excess heat and water usage in pulp and paper mills has been the subject of several studies. Within these studies is the one produced by Ashton (1986). This author used novel techniques based on Pinch technology to evaluate the impact of using new equipment in different parts of the process. On the other hand previous studies also evaluated the impact of a reduction of water consumption by closure of water loops in energy consumption (Wising *et al.*, 2002). There are also techniques, similar to Franck (1999), which focus only on the reduction of energy and consequently on the costs and investments. However, all of these authors based their work on Process Integration.

1.1. Objectives

The main objective is the evaluation of the energy used in the mill to identify the potential for energy savings: And, consequently, the environmental impact and structural modification in the process. The Pinch technology was used as a tool for the identification of a potential saving of energy. This analysis has been recently used in the pulp and paper industry (Franck *et al*., 1999 and Bengtsson, 2002), but its application has been in chemical and petrochemical industries. In the industry of pulp and paper, this method may not be direct because of the industry's unique mix of operations and the minimum area concept of Pinch analysis.

There are several techniques based on the minimisation of the environmental effect. Some of the authors argue that the closure of the water loop reduces water consumption and consequently the consumption of steam (Edelmann, 1999). This reduction leads to a reduction in the emission, wastewater, and water used. The combinations of Energy Pinch analysis, water Pinch analysis, and both together, and further simulation of the projects, is also defended by Savulescu *et al*. (2000). Other techniques are just based on t energy consumption and its reduction (Wising, 2002). A reduction in the heat demand leads to a surplus of heat available. This fact also means that fuel (oil, gas) can be saved and consequently the environmental impact lessened.

Another objective arises as a consequence, the determination of the economic feasibility of energy savings. The cost analysis for this type of investment is fundamental for the pulp and paper industry.

2. Process Description

According to Martins & Barata (2003) process description the Kraft process is divided in two main areas. One is the fibre line that is sub-divided into two: wood handling and pulp production. The chemical recovery is the other part. This involves the recovery of white liquor and energy recovery from black liquor. This line also produces green liquor from the dissolution of smelt in weak white liquor and weak white liquor from a slacker and Causticizers.

The production of chlorine dioxide using SVP-Lite process, energy production and wastewater treatment are also part of the global process. These processes work in parallel with the main process and are continuous processes.

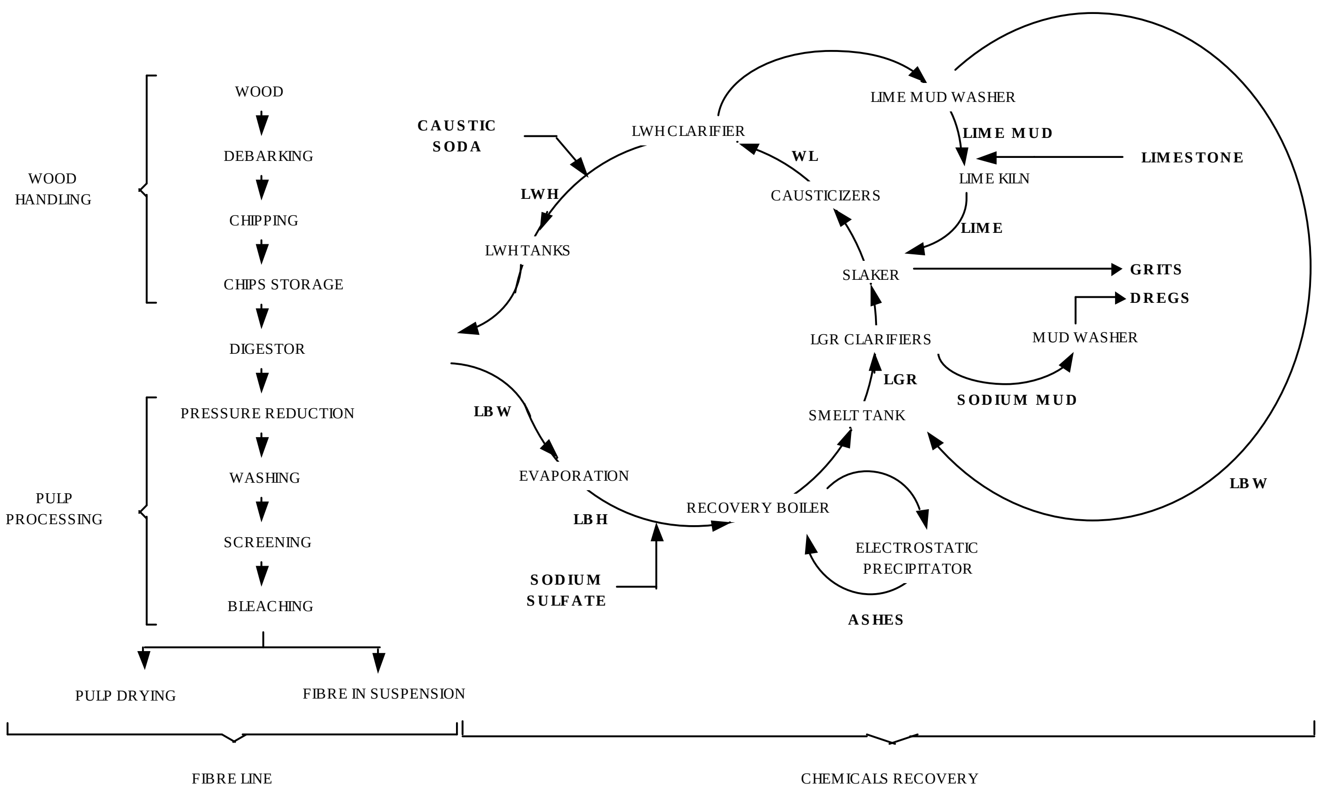

Figure 2.1 - Global Kraft Process. (Martins & Barata, 2003)

2.1. Fibre Line

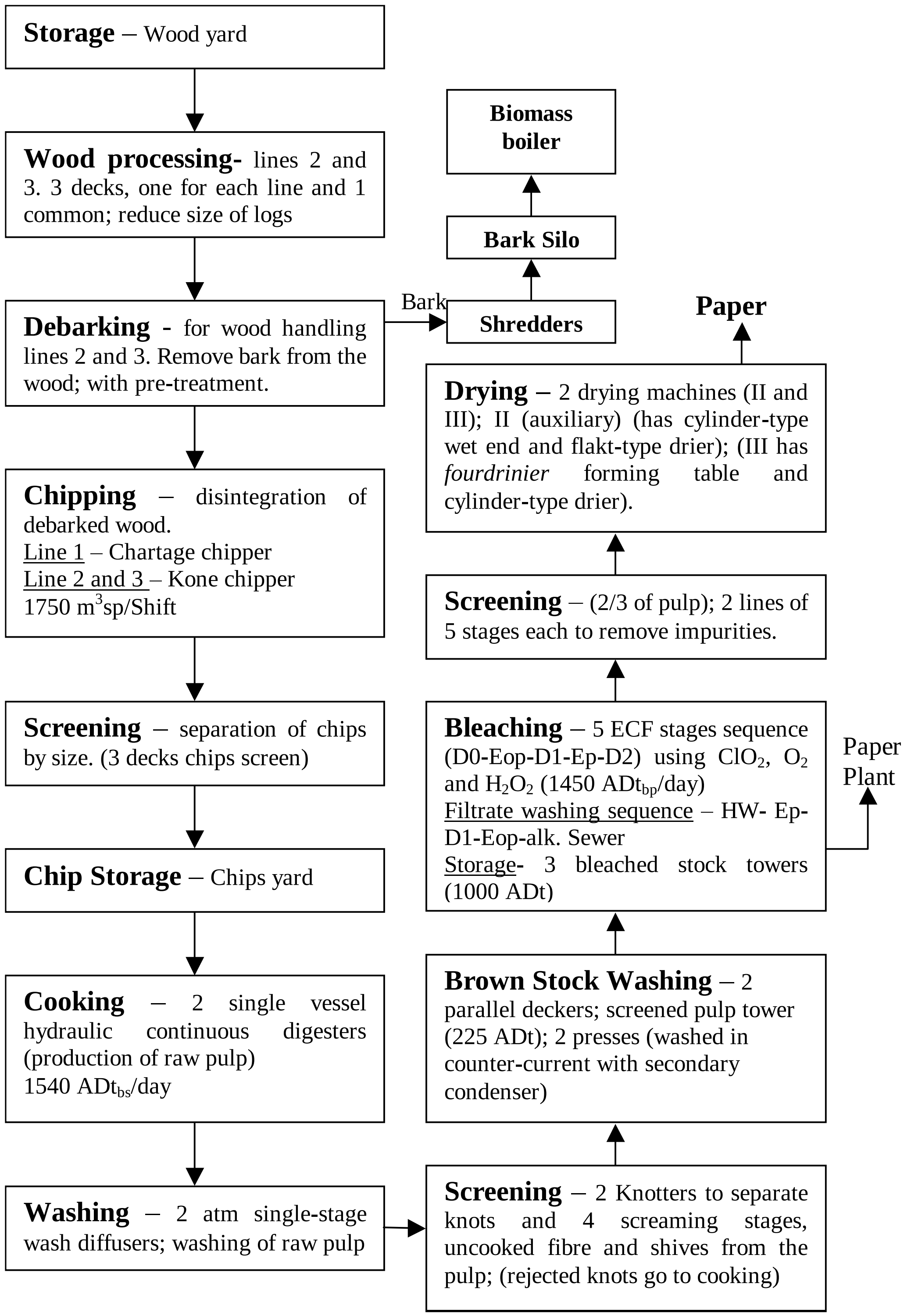

Figure 2.2- Summary of the different stages at the Fibre line.

2.1.1. Wood Handling

The wood used in the PORTUCEL process is Eucalyptus. Part of this wood is national (75 %)and part of it is imported (25 %). The national type of wood is *Eucalyptus globules*) and the imported is *Eucalyptus urograndis* mainly from South America (Brazil).

The wood separation is described by Martins & Barata (2003) in three lines. Line number one is the oldest one and it only processes debarked wood. The other two lines can process wood with or without bark.

The wood is first debarked to produce debarked logs. The bark removed to the bark boiler. The logs are then washed and sized and taken to the chipping machine, which transforms logs in to small chips. The chips produced are then separated in a vibrating screen and the accepted chips are storage in the chip yard for pulp production.

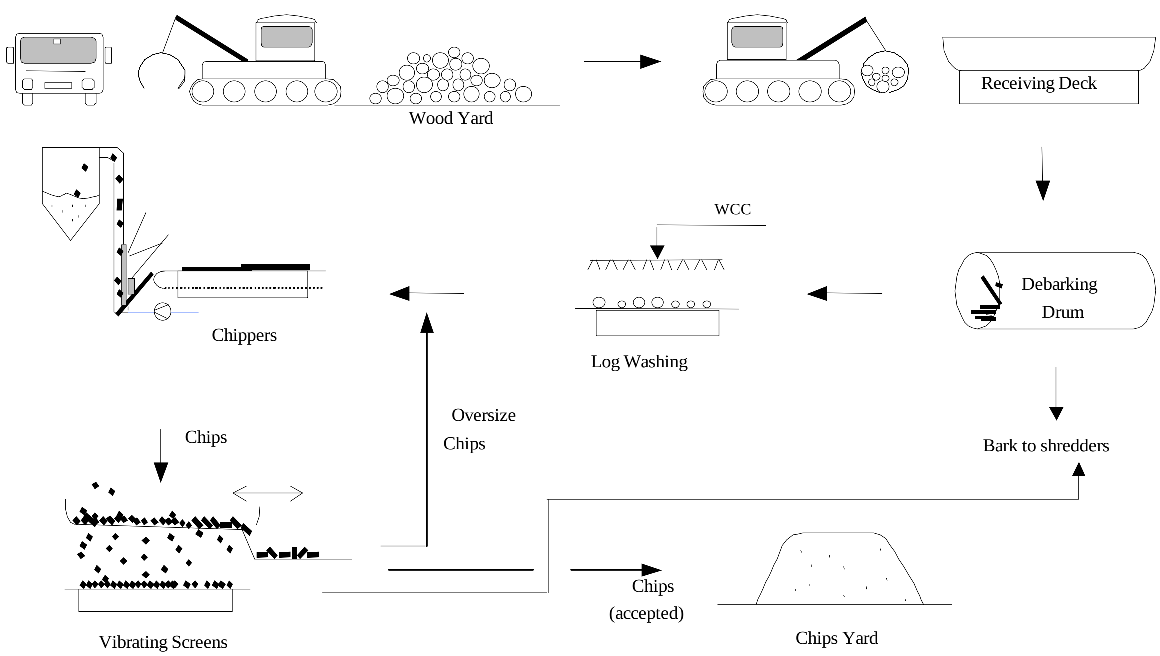

Figure 2.3- Wood-handling process. (Martins & Barata, 2003)

2.1.2. Continuous Cooking

In agreement with the information given by Martins & Barata (2003) Cooking is held in two continuous digesters (pressurised vessel used for cooking chips for pulp). Both processes are similar and each one has one single-vessel hydraulic continuous digester.

The chips from the chip yard are fed to a common silo where they are divided into digester I and digester II. In the feeding line, chips are impregnated with steam and are fed to the digesters. In the digester occurs the impregnation with white liquor, after which the chips are heated and cooked at 155 to 160 ºC. The digester operates by extended cooking (co and counter-current cooking) with a short wash in the lower part of the digester. After this unbleached pulp is obtained.

Each digester has four heat exchangers. The exchangers are placed in series of two (one series at the top and the other at the bottom). The function of these exchangers is heating the digester, through the black liquor that is introduced in the digesters. The exhaust black liquor is extracted and passes through two flash cyclones and a fibre screen. The black liquor from continuous cooking I is mixed with the black liquor from cooking II after the fibre screens and at the black liquor cooler. Excess water is then separated from the black liquor to produce heavy black liquor of a concentration good enough to burn in the recovery boiler.

2.1.3. Brown Stock Washing

In PORTUCEL and according to Martins & Barata (2003) process description, the pulp produced is first washed in the digester and then goes to two atmospheric single-stage wash diffusers, one for each digester.

The uncooked fibre and shives are separated in two parallel knotters from the pulp and are screened in four stages .The rejected knots are introduced again in the cooking. This pulp then passes through two deckers in parallel followed by two presses. The pulp from the second press has a consistency of 25 to 30 %, and is then diluted with white water.

Pulp washing is counter-flow to separate spent pulping chemicals using secondary condensate from evaporation in the last press wash. Biermann (1996) stated that this model allows better removal of pulping chemicals and lignin with less water than usual. This fact can reduce bleaching chemical demand.

The pulp washing requires a liquid with certain levels of COD and temperature to maximise the mass transference and solids solubility.

2.1.4. Bleaching

"*Bleaching is the treatment of wood (and other lignocellulosic) pulps with chemical agents to increase their brightness*". (Biermann, 1996, p123) It is normal in this kind of bleaching that the uses of compounds containing chlorine or oxygen are used and then the extraction of alkali in several stages.

According to Biermann (1996) the use of several stages (normally 3 to 7 stages) with different compounds increase the brightness of the pulp, this means that the efficiency of bleaching is increased with the reduction of chemical required. In this process is used a 5 stage ECF bleaching (D0, Eop, D1, Ep, D2) with a split in two parallel lines to Eop and D1 stages. Each stage consists of a pump (mixing chemicals with pulp), a retention tower (bleaching chemicals to react with pulp) and a washer (removing bleaching chemicals and solubilising pulp compounds). The D stages are intercalated with E stages for extraction. Chlorine dioxide is added to D stages as an oxidizing agent, which reacts with lignin. Extraction stages are performed with sodium hydroxide, reinforced with amounts of peroxide and oxygen at Eop stage.

The filtrate from the next stage is used as a washing liquid in the later stage, except in E2 and D2 (these are the washing liquor feeding stages). In E2 is used hot water (WC75) as the washing liquid in counter-current and in D2 is used white water (WW) from the drying machine. Filtrates of D stages are acid filtrates and from E stages are alkaline filtrates. Theoretically the sequence would be WW-D2-D1-D0-acid sewer and WC75-E2--E1-alkaline sewer. However, in PORTUCEL Setúbal, the E2 filtrate is used in D1 stage and the D2 filtrate jumps to the D0 stage in order to decrease the pH in E1 stage (its filtrate is from a D stage) and to avoid carbonates precipitation.

The bleached pulp is then screened in two lines, each with five stages.

2.1.5. Drying

Part of the bleached pulp (approximately 1/3) is pumped at low consistency to the paper plant, the rest of it goes to cleaning. This cleaning is done in two lines of screens, each one with five stages.

According to Martins & Barata (2003), the drying line has two drying machines (II and III). Drying machine II is just an auxiliary machine and it is *flakt* type or air borne type with one cylinder-type wet end. The other one produces more then 90 % of the total production of pulp and it is cylinder-type with *fourdrinier* forming table.

Pulp drying machine is a unit for continuous forming, dewatering and drying a web of pulp fibres.

A forming table is where the sheet, to be pressed and dried, is formed. Biermann (1996) explained that the cylinder-type wet end consists in one or several rolls freely revolving over which the wet sheet is moved towards the dryer section.

The same author also explains that the *fourdrinier* wet end forming table consists in a large blade followed by smaller blades (vacu-foils) with gaps between them. Under the *fourdrinier* wire, rolls exist to support the wire and wet web weight.

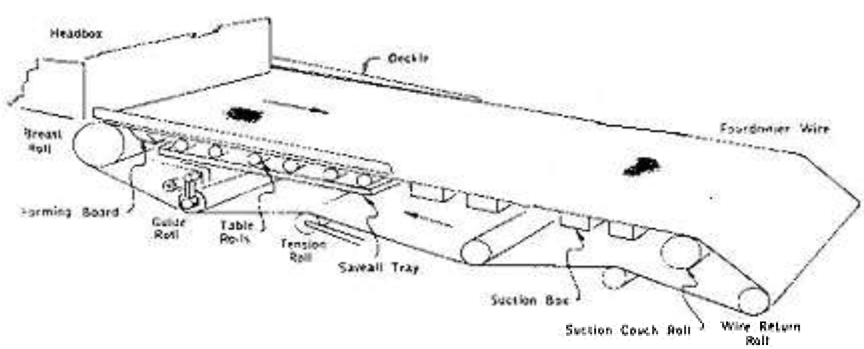

Figure 2.4- Diagram of a pulp *fourdrinier* wet end forming table.

After the forming table, the presses are fundamental to removing the excess water in the pulp. Each press is composed of press rolls with the function of removing water, smoothing and compressing the pulp. A diagram of a press is represented below.

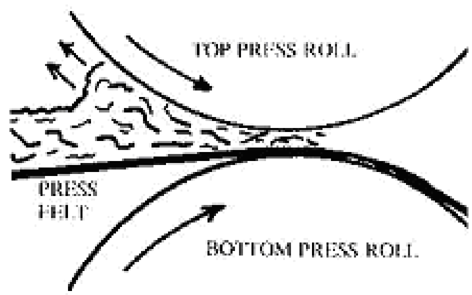

Figure 2.5- Schematic representation of the press process (Biermann, 1996, p 236).

In this section, should be removed as much water as is possible. This leads to less water required to be removed in the dryer, giving a higher production rate with lower energy costs (steam costs).

The function of the dryer section is evaporation of water from the sheet. This is obtained by adding heat to the sheet and circulating air through the dryer enclosure. In this case the cylinder-type dryer section is composed of three stack cylinder divided into seven steam supply groups (96 cylinders overall). Each cylinder is filled with steam (LPS I) to heat the web. The circulation of air is also very important because it prevents an undesirable displace of water from the web. The use of several cylinders is explained by Biermann (1996), based on the fact that the web is dried on one side and the other side, alternating between cylinders. The temperature of the first group is also very important. Very high temperatures may produce irreversible damage to the pulp and further more change the quality of pulp.

This dried pulp sheet with just 10 % of humidity is then cooled till 35 ºC, cutter, baled, stacked and it goes to the market.

2.2. Chemical Recovery

Chemical recovery is the process that recovers and regenerates inorganic chemicals used in pulping. This process involves recovery of the inorganic cooking chemicals (Na_2CO_3 and Na_2SO_4 in the black liquor converted to NaOH and Na_2S white liquor), regeneration of heat energy by combustion of organic materials from wood, reduction of emissions by transforming waste products in to useful materials and regeneration of inorganic chemicals into pulping chemicals.

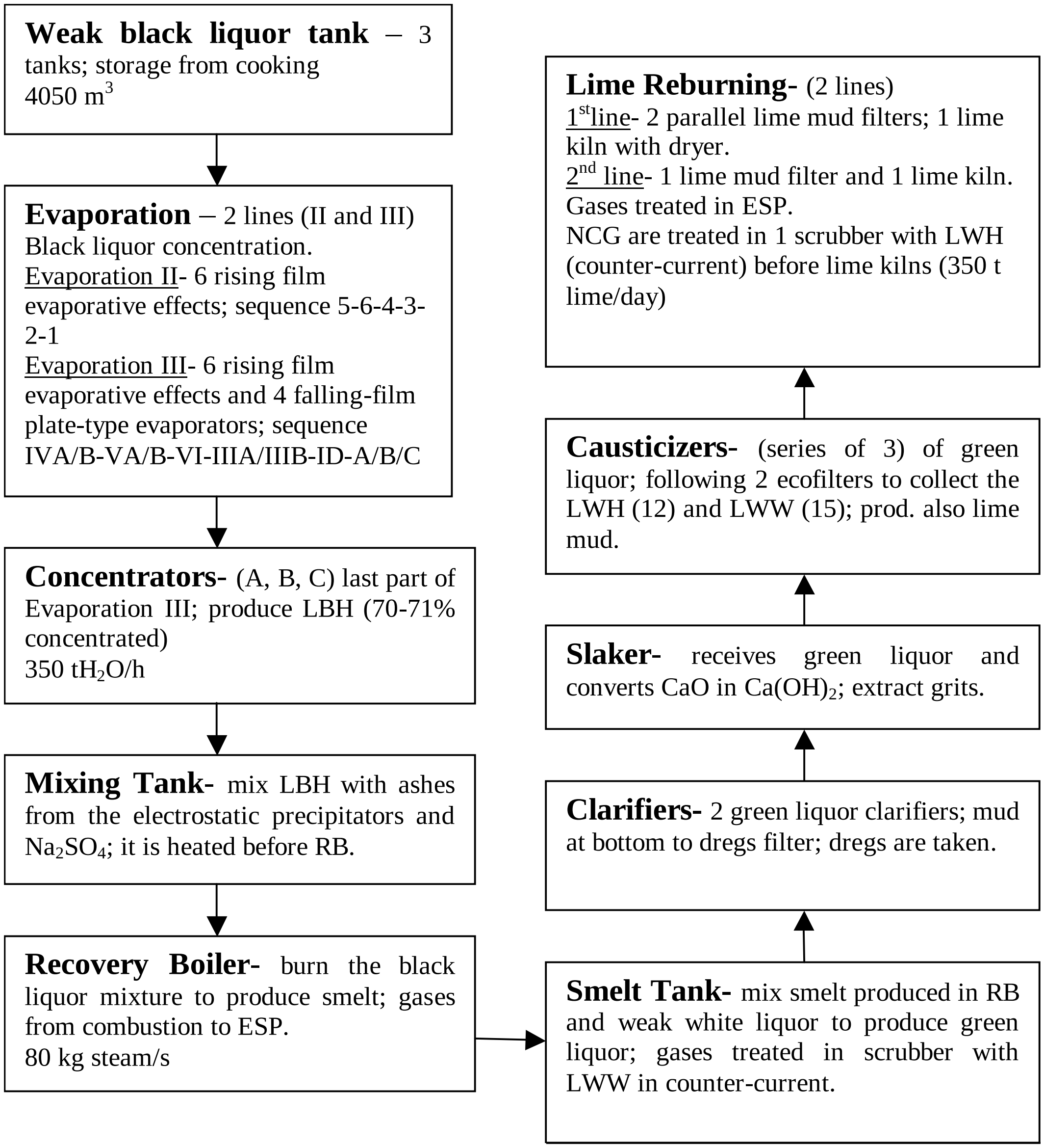

Figure 2.6- Diagram for chemical recovery.

2.2.1. Evaporation

In Martins & Barata (2003) description of the process, a mixture of weak black liquor (15-17 % in D5) rich in organic material, Na_2SO_4, and Na_2CO_3 that comes from the cooking line is fed to two lines of multiple effect evaporators. The function of the multiple effect evaporators (MEE) is to concentrate the black liquor as much as possible so that heat recovery from liquor combustion can be as efficient as possible. Biermann (1996) defends that an increase of solids concentration is also favourable because it decreases the smelt production and decreases sulphur emissions.

Evaporation II and III consist in six Long tube vertical (LTV) Rising-film effects. However Evaporation III is also composed by more Falling-film plate type evaporators (Martins & Barata, 2003).

A Long tube vertical (LTV) Rising-film evaporator is described by Biermann (1996), as a long vertical tube where black liquor rises up in the heat exchangers area, till it reaches the vapour dome (top of the effect). At the top of the effect (vapour dome), the steam present in the black liquor flashes and is pulled by vacuum to the next effect. A schematic representation of a LTV Rising-film is shown in the figure below.

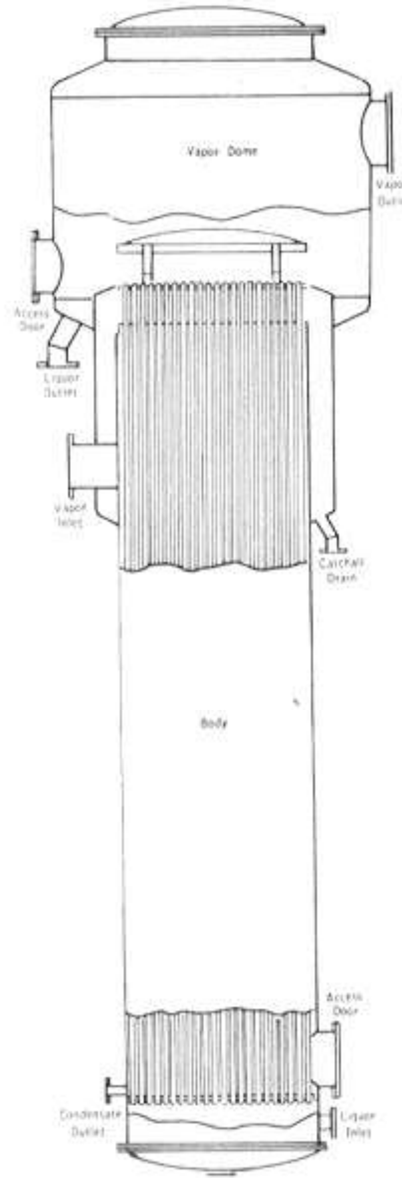

Figure 2.7- Long tube vertical (LTV) rising evaporator (Biermann, 1996, p 105).

A Falling-Film Plate-type evaporator consists of a top and bottom chamber and several vertical plates. Condensate and non-condensate are recovered at the bottom of those plates. On the outside of the plates, black liquor evaporation occurs. Black liquor is fed through a distribution chamber on the vessel top and falls between the (steam) plates. The vapour escapes to the sides (beyond the plates set), exiting from the vessel top, and the liquid is gathered at the bottom, and then pumped to the next effect.

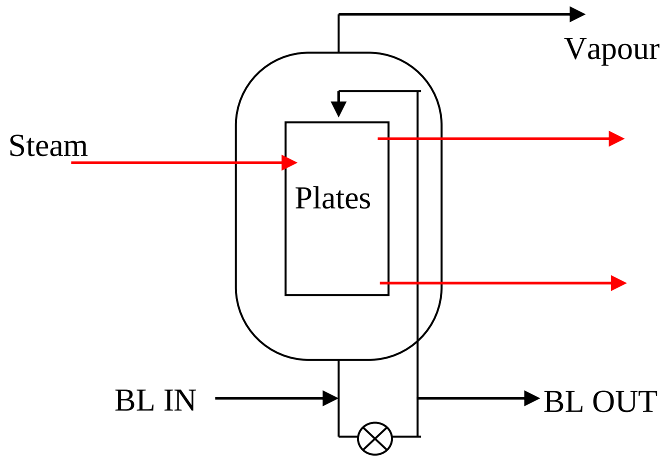

Figure 2.8- Schematic figure of a Falling-film plate-type effect (Martins & Barata, 2003).

According to Martins & Barata (2003) in Evaporation II the weak black liquor follows the sequence of effects: 5-6-4-3-2-1 (backward feeding). The intermediate black liquor formed is fed to a tank where it is split into two parts: one part that is mixed with the intermediate liquor from the second effect of evaporation III; the other part is fed to the chemical products line.

In agreement with the description given by the authors mentioned before, Evaporation III follows IVA/B-VA/B-IV-IIIA/IIIB-II-IA/B/C. The heavy black liquor obtained has a concentration of solids between 70 to 71% and is fed to the Recovery Boiler for combustion and production of high pressure steam.

The condensate from each evaporation line (foul condensate) is mixed with the condensate from cooking and is sent to a stripping column for purification. The condensate from the striping column is then mixed with the condensate from the evaporation lines and is used in brown stock washing and lime mud washing.

2.2.2. Recovery Boiler

‘*The purpose of the Recovery Boiler is to recover the inorganic chemicals as smelt (sodium carbonate and sodium sulphite), burn the organic chemicals so that they are not discharged from the mill as pollutants, and recover the heat of combustion in the form of steam’.* (Biermann, 1996, p 107)

The concentrated black liquor from Evaporation is mixed with ashes from the electrostatic precipitators and with the make-up sodium sulphate in a mixing tank. This is heated with MP steam. The heated mixture is fed to the Recovery Boiler. (Martins & Barata, 2003)

Marklund (2002) defends that, to extract the chemicals and energy from the black liquor in an efficient way, it has to be atomised into droplets and sprayed into the recovery boiler. The mixture of black liquor droplets fed to the recovery boiler, is exposed to hot gases and is submitted to drying, pyrolysis and char conversion.

Biermann (1996) explains that the recovery Boiler is divided into three zones: oxidizing zone (upper section), drying zone (middle section where the black liquor is fed) and reducing zone (bottom section where the sulphur compounds are converted to Na_2S). In the bottom section the NaOH and sodium salts of organic acids are transformed into Na_2CO_3. The main chemical reactions in this unit are:

Sodium salts conversion:

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$$

Make-up chemical reduction:

$$Na_2SO_4 + 4C \Leftrightarrow Na_2S + 4CO$$

The reduction of the make-up chemicals happens in the bottom section because it is poor in oxygen. The oxygen required for the combustion is supplied by pre-heated primary air (AP). The AP is heated using a series of two heaters (I and II). The heater I uses LP steam to heat it from 22.5 to 114 ºC and the heater II uses MP steam to heat it from 114 to 153 ºC. This AP has the function of burning the organic compounds, maintaining the reduction conditions. The second zone is above the one described before. This zone uses secondary air (AS) that is heated by a series of two heaters, like the AP. In this case steam is used to heat the air from 23 to 166 ºC. In this section it is recommended that air be in excess for a complete combustion of the organic materials. The top section should be under oxidative conditions to prevent carbon monoxide emissions.

In this process and in agreement with Martins & Barata (2003) description the gases formed by combustion are drawn to three electrostatic precipitators. Electrostatic precipitators (ESP) consist of a chamber filled with metal plates, through which the gases pass. In the chambers the particles suspended in gas are removed. In this way the gas is purified before being discharged into the atmosphere.

The smelt that is produced in the boiler goes to a smelt tank where it is dissolved into weak white liquor producing green liquor. The gases produced in the smelt tank are treated in a scrubber with weak white liquor.

2.2.3. Causticizing and Lime Reburning

The green liquor produced in the recovery boiler process is fed to a stabilizing tank. At this point the density of the green liquor is used as a control variable for the concentration of it. This green liquor goes to two clarifiers. "*A Clarifier is a settling tank used to remove dregs by sedimentation before the green liquor is recausticized*." (Biermann, 1996, p112) The mud settles at the bottom of the clarifier and is then removed and fed to the dregs filter. The dregs are undissolved materials in the green liquor and are constituted of carbons and foreign materials (insoluble metals carbonates, sulphates, sulphides hydroxides, nonwood fibres, silicates).

The purified green liquor goes to a slaker where it is transformed into lime liquor by addition of CaO. Then the lime liquor formed in this unit goes to a series of three Causticizers. (Martins & Barata, 2003)

A causticizer is a continuous flow, stirred tank reactor, in agreement with Biermann (1996). From the description provided by Martins & Barata (2003), the lime liquor is stirred using a pitched blade turbine. This liquor passes through a series of Causticizers and is fed to a tank where it is mixed with heavy white liquor that is produced in ecofilter 1. This liquor goes to the ecofilter 1 where, as was said, is heavy white liquor produced. The heavy white liquor is stored in two tanks where caustic soda make-up takes place.

The lime mud ($CaCO_3$) extract in the ecofilter 1 goes to a lime mud dilution tank where is mixed with secondary condensate (or hot water) to wash and weak white liquor produced in the ecofilter 2. This mixture goes to the ecofilter where is formed weak white liquor. LWW then goes to two storage tanks and then to a cooler before being fed to the smelt tank.

The lime mud ($CaCO_3$) from the ecofilter 2 goes to a mixing tank where it is washed with hot water or secondary condensate. The diluted mud goes to two lines of Reburning. The first one consists of 2 parallel lime mud filters and one limekiln; and the other consists of one lime filter and one kiln. The filter has the function of removing entrained alkali and lime thickening.

In the kilns, lime mud ($CaCO_3$) is dried, heated and converted into CaO, according to the chemical reaction:

$$CaCO_3 \rightarrow CaO + CO_2(g)$$

The fuel oil combustion supplies the energy required to achieve the desired temperature required. Inside the kiln the combustion gases flow in counter-current with the lime. The non-condensable gases from the continuous cooking line and evaporation lines have to be treated in a scrubber with heavy white liquor, in counter-current, before being introduced into the kiln to avoid ‘ring formation’. The exhausted gases from the kiln are treated in an electrostatic precipitator.

The fuel oil used was pre-heated in two parallel pre-heaters from 46 to 113 ºC.

2.3. Chemical Products

According to Akzonobel Eka Chemicals (2000), the production of chlorine dioxide using the SVP-Lite process is based on the reaction between methanol, sodium chlorate and sulphuric:

$$9NaClO_3 + 2CH_3OH + 6H_2SO_4 \rightarrow 9ClO_2 + 3Na_3H(SO_4)_2 + \tfrac{1}{2}CO_2 + \tfrac{3}{2}HCOOH + 7H_2O$$

Reactants concentrations are very important in this process. Their concentration should be kept high so that the yield and efficiencies are constant.

In agreement with the description made by Martins & Barata (2003) the sodium chlorate is diluted with water in a dissolution tank. The diluted sodium chlorate ($NaClO_3$) is then mixed with methanol and fed to the generator. The filtrate of the reboiling-ring side-stream filtration is added to the generator product solid stream [$Na_3H(SO_4)_2$] and concentrated with LP steam in the reboiler. The reboiler output stream is fed again to the generator.

The gas leaving the generator consists mainly of chlorine dioxide and water vapour. This vapour is cooled in the generator condenser with water. The remain chlorine dioxide gas is absorbed in an absorption tower where water is in contact with the gas to produce strong chlorine dioxide. This chlorine is then added to that condensed in the condenser and is sent to four tanks, for use in the bleaching process.

The tail gas from the absorption tower goes to the process condenser to be condensed and sent again to absorption. The gas that is not condensed goes to a scrubber, which is used to wash the gas at atmospheric temperature and to remove the chlorine dioxide existent in the vented gases. The effluent water from the scrubber is also fed to the tower, so that the chlorine dioxide present in the vent gases can be recovered. The crystals ($Na_3H(SO_4)_2$ and a little content of dissolved ClO_2) formed in the generator, are fed to an acid sulphate filter to remove it as a nearly dry solid. The salt cake ($Na_3H(SO_4)_2$) obtained is then dissolved and neutralised with caustic soda in a dissolution tank. The solution formed, goes to the sodium sulphate filter (second filter). The cake produced in the second filter is finally mixed with intermediate black liquor from the Evaporation line II and is fed to Evaporation line III.

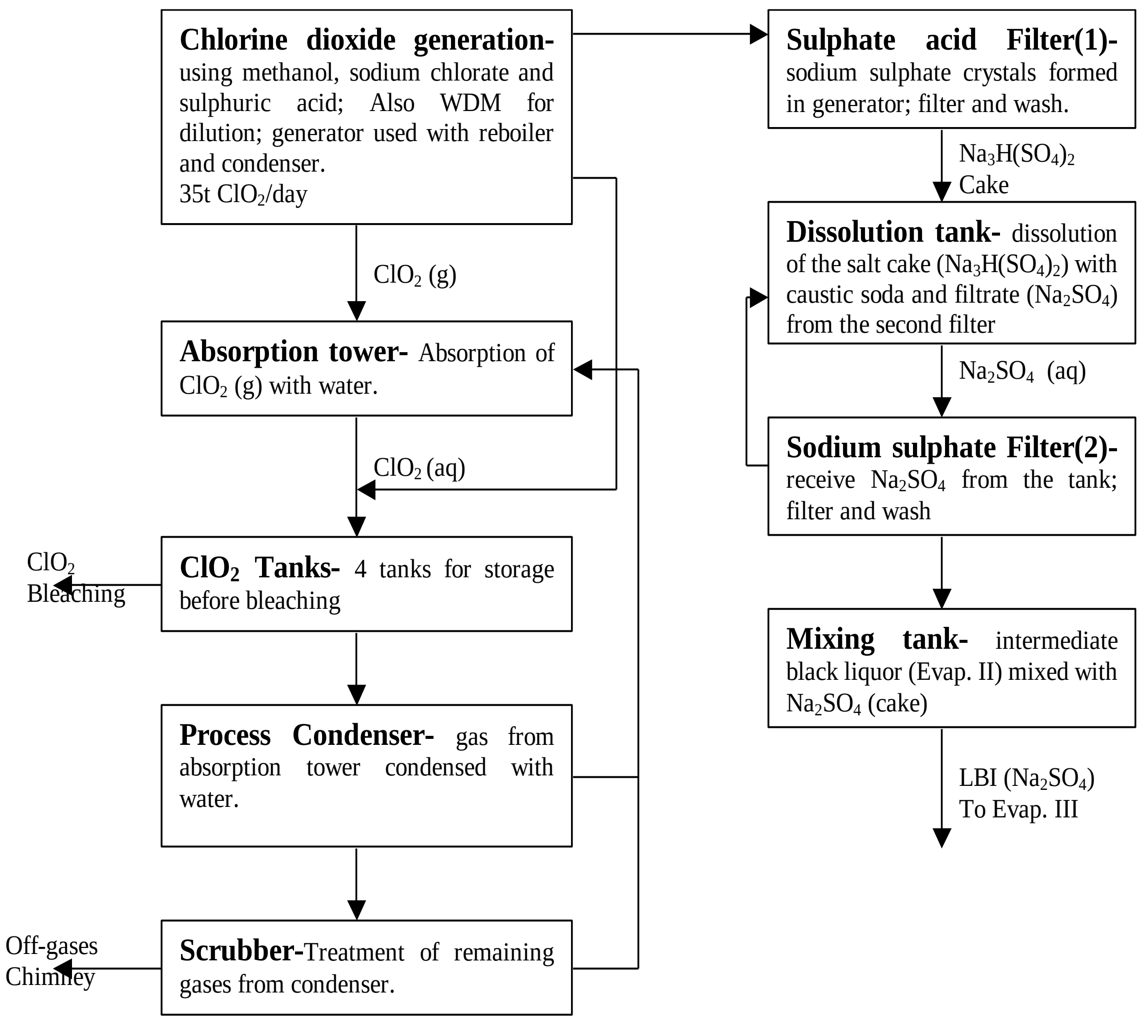

Figure 2.9- Diagram of the chemicals production with SVP-Lite process.

2.4. Energy Production

The production of energy is one of the most important parts. Energy is used in almost all the lines.

In PORTUCEL and in agreement with Martins & Barata (2003) description, the Recovery Boiler and the Bark Boiler support the steam production. Bark and sawdust from the Wood Handling is fed to two Bark Shredders. In the Shredders big pieces of bark are shred into the size required for the boiler. The shredded bark goes to a Bark Silo where it is stored and from there fed to the Bark Boiler. The Bark Boiler burns the bark and the gases from the combustion go to an electrostatic precipitator. The combustion of bark in the presence of water induces the formation of steam, in this case HP steam that goes to the Steam collector. In this process there also exists an auxiliary Fuel Oil Boiler that assists the mill start-up.

The steam from the collector is then fed to the Condensation Turbine, which has the function of pressure reduction and power production.

The power is produced by two Steam Turbines (II and III). Turbine II is an auxiliary back pressure turbine with a capacity of 33 MVA and its extraction are with MP steam and LP steam II. Turbine III is a Condensing Turbine with a capacity of 55 MVA and the extractions are MP steam and LP steam II and I. The extraction of LP steam I is used on the drying machine III.

Table 2.1- Steam produced and used with respect to absolute pressure in (kPa).

Steam	Pressure (kPa)
HP	6201
MP	1150
LP I	601
LP II	461

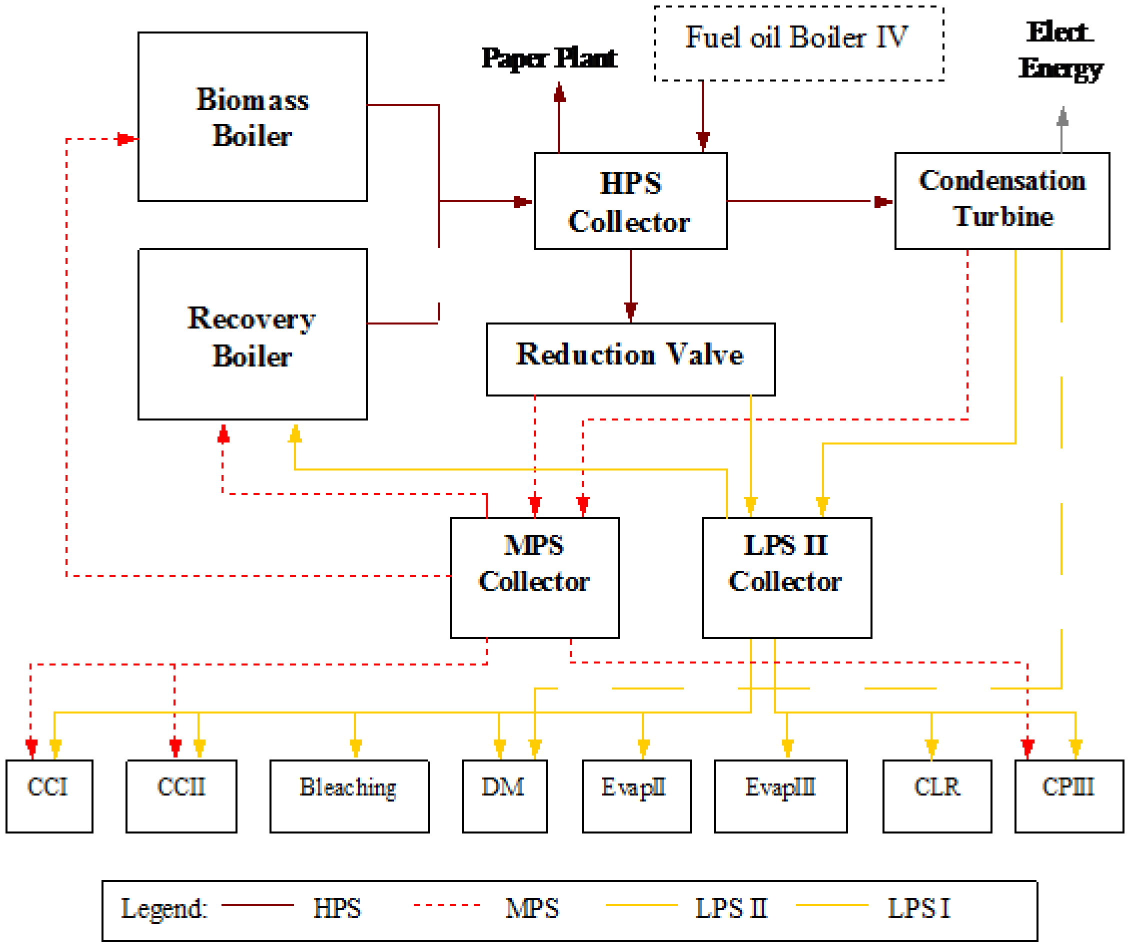

Figure 2.10- Energy and steam consumption and production.

2.5. Wastewater Treatment

The Water Environment Federation (2000) explains that the alkaline wastewater is first submitted to primary treatment, which is the removal of floatable and settable solids. This treatment consists in the use of bar screens, grit removal, flocculation, sedimentation and dehydration of sludge. The secondary treatment is a biological removal of dissolved solids, based on the activated-sludge process. The activated-slug process consists of the addition of decomposing bacteria with agitation to dissolve oxygen.

According to Biermann (1996), the alkaline sewer is the mixture of wastewaters from all the lines in the general process. This mixture first passes through a bar screen to remove same of the largest particles, then through a grid removal so that the remaining particles are removed. To assure that all the non-soluble material is removed, it goes to flocculation for further primary sedimentation. In the primary sedimentation the primary sludge is taken and is sent to a 'Klein' press. The solution with soluble material goes to the mutual neutralization where urea, acid sewer and calcium hydroxide are added to adjust the pH. This mixture is then sent to two cooling towers, followed by the aeration tank. In the aeration tank, two compressors supply air and the decomposing bacteria degrades the organic compounds of the sewer. The micro organisms are removed in the secondary settling tank. The biological sludge goes to a sludge thickener followed by the mixed sludge silo and finally to the 'Andritz press'. The pressed sludge from the 'Klein' press and from the 'Andritz' press goes to sludge treatment. The solution removed from the pressed sludge and from the thickener returns to the mutual neutralization for further treatment.

3. Process Analysis

The aim of this study, as it was mentioned before, is the reduction of water and energy consumption in the production of pulp.

3.1. Overall Analysis

PORTUCEL pulp production is an atypical production. For example, two continuous digesters hold the cooking line and the impregnation of the chips with the liquor is done inside the digester. In a “The Eco Cyclic Pulp Mill” (wising, 2003) the impregnation is done in a separate vessel. The three flash chambers used in this mill are substituted by two flash chambers in PORTUCEL with the same static conditions. As in “The Eco Cyclic Pulp Mill” the black liquor leaving cooking plant, in PORTUCEL, also has the temperature for the evaporation plant. The production of steam from the black liquor and the condensate system connected with the digester form a possibility for heat exchanger.

Dryer plant in PORTUCEL is divided in an auxiliary part where is used an air borne dryer and the main part where is used a cylinder type dryer. In “The Eco Cyclic Pulp Mill” (wising, 2003) the dryer is just one and is air borne type. Previous researches have been done over steam type dryers where the steam consumption at this stage has been successful reduced. In PORTUCEL drying process there is a possibility for heat integration in the heat exchangers system surrounding the dryer.

PORTUCEL evaporation plant is composed by two lines each with six rising –film effects and one of them with more four falling-film plate type evaporators. A typical evaporation plant is only composed by six-effects (counter-current). In PORTUCEL process is used low pressure steam in contrast with the medium pressure steam used in “The Eco Cyclic Pulp Mill” (wising, 2003). The Evaporation plant is considered as a black box, however there is possibility for heat exchanger in the condensers system.

A closed water circulation is used in PORTUCEL. This was defended by almost all the authors present in the Literature Review Chapter as a god way for water use reduction in the mill. However, in PORTUCEL case, when compared with other mill consumption is still the higher. The problems of big water consumption are the large flow of wastewater for treatment, environmental conditions and the amount of steam spend to heat the water (warm and hot water). In PORTUCEL pulp production the water that is circulating in the in all the stages is heated using the surplus of steam from each stage, stored and use in another part of the mill. From this explanation it is possible to conclude that a reduction in the water consumption is only possible with the identification of a excess of water usage in a particular stage.

3.2. Drying Process Analysis

In the first analysis of the PORTUCEL pulp plant and, based on previous studies, presented in the literature review (chapter 4), it is possible to assume that a reduction in steam consumption in the drying process will induce a reduction in the required steam production.

In the Drying Machine process, the moist hot air that is withdrawn from the drying section hood enclosure is used in the heat exchangers to heat the hood supply atmospheric, or machine room, air and water: the cooled moist air is then released into the atmosphere. This use of the hot air extracted leads to a reduction in steam consumption.

The condensate formed in the heat exchangers has a temperature of approximately 149 ºC and is used in the boilers to reduce make up treated water requirement. That may offer a possibility to be used as hot fluid and in this way reduce the consumption of water and steam to heat up the water.

The drying process is represented in figure 3.1.

An amount of reject heat has been identified in the drying process and the use of this heat in another part of the pulp mill apart from that shown above is possible with a redesign of the heat to the recovery process

When the consumption of water in PORTUCEL is compared to the consumption of water in the Scandinavian pulp and paper industry, a surplus of water usage is identified in PORTUCEL. Reductions of hot and warm water required lead to a reduction in the steam spent to heat the water. A possibility of using the existing condensing steam to heat the water must be considered. Another advantage in water required reduction is the reduction of the effluent flow rate and treatment costs.

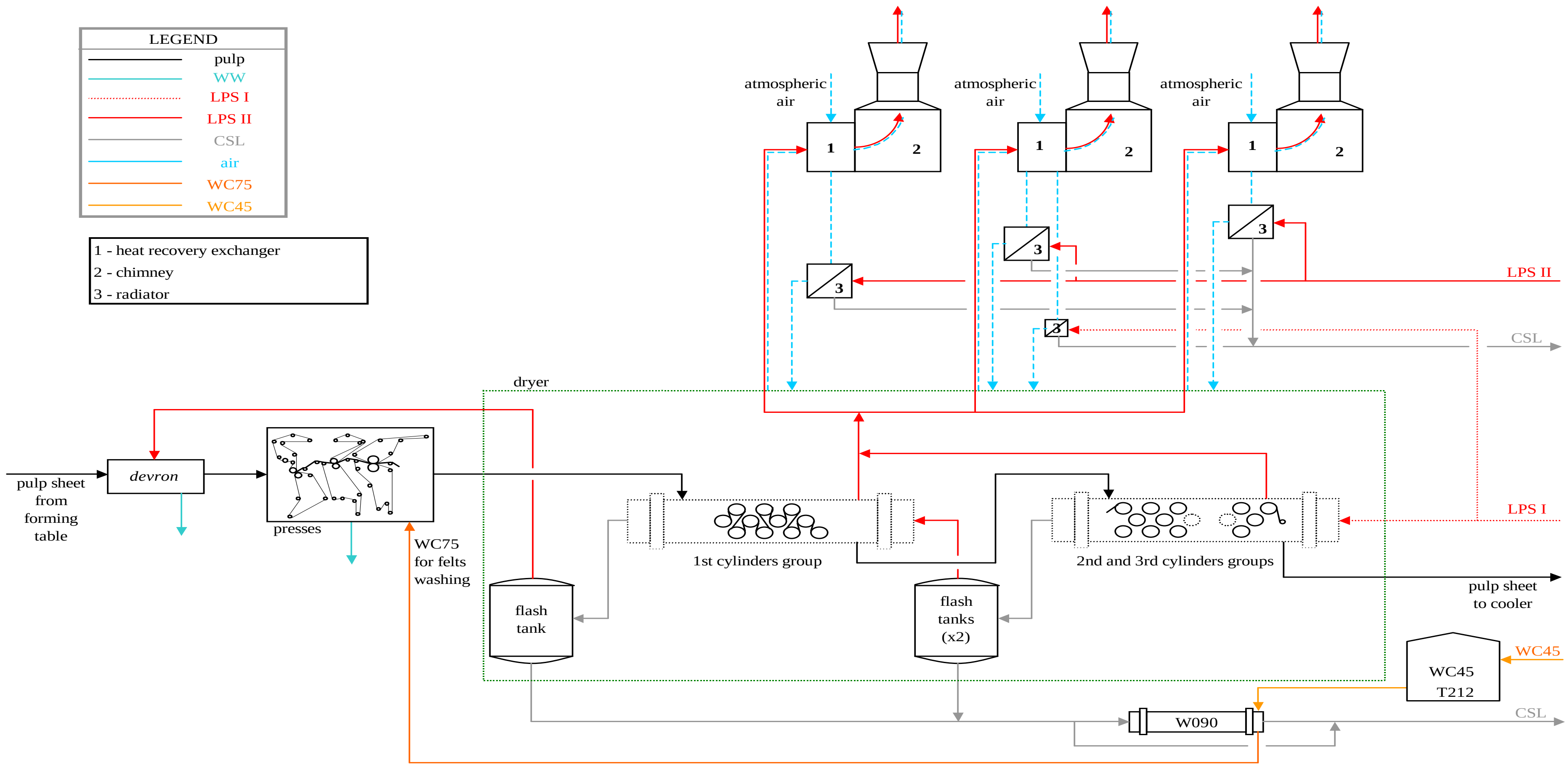

Figure 3.1- Drying Machine (Martins & Barata, 2003).

4. Literature Review

The heat exchanger network is an important part of the chemical plant design. In the 'onion diagram' the heat exchange network and utilities are the outer part of the onion Figure 4.1.

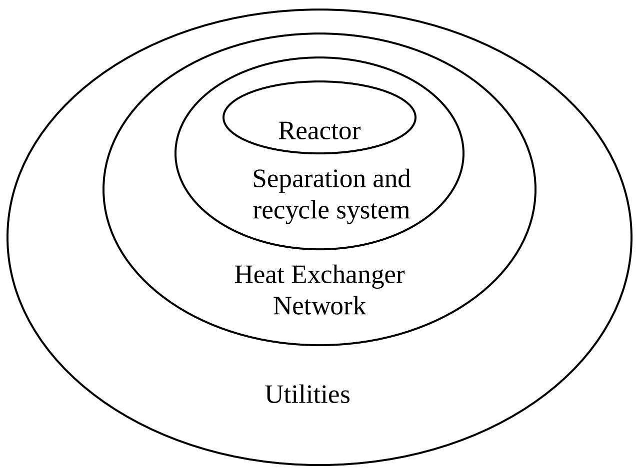

Figure 4.1- The process design 'onion diagram'.

All the units in the centre of the onion (reactor, separation and recycling system) have hot and cooling duties.

For an initial design, targets can be set in respect to the heat exchanger network and utilities. These targets make possible the energy and capital costs savings for the outer layers. It is also possible with targeting to suggest changes in the middle layers to improve the energy and capitals savings of the heat exchange network and utilities (Smith, 1995).

4.1. Heat Exchanger Network

The Heat Exchanger Network (HEN) of a given process is the point. It makes possible it to evaluate changes in the processes.

In 1978, Linnhoff and Flower proposed a new synthesis method called Temperature Interval or 'TI' method, which used the fact that desirable network structures are features of high degrees of energy recovery. This approach was based on thermodynamic theory and the problem was solved in two stages. In the first stage preliminary networks with maximum heat recovery were generated. In the second stage the preliminary networks produced in the first stage were used as starting points. Within the creation of this method was also used for the Problem Table Algorithm and the Grid Diagram. However, in this case, 'Process Synthesis'; the study was based on heat recovery rather than costs.

Later, in 1979, Linnhoff and Flower described how a modification in the Thermodynamic Second Law could overcome constraints such as temperature-limits, safety precautions and start-up capability. The proposed modification was presented, before being brought to consideration costs. In this study, two important parameters were taken onto account: driving force and load. The determination of the equipment cost was based on those two parameters.

The design of the heat exchangers network evolved with the presentation of a novel method. This method was called 'pinch design method' (Linnhoff & Hindmarsh, 1982). The scope of this study was the placement of process and utility heat exchangers to heat and cool various streams with the objective of minimising total costs (capital and operating costs). The objective mentioned before was achieved in two stages. The first stage found the minimum energy recovery for a specific ΔT_{min}. The second stage aimed for a reduction in the number of units. The pinch design method was capable of identifying stream splitting for a minimum utility design.

The 'pinch' placement in a Heat Exchanger Network and the minimum utility requirement can be identified using the problem table algorithm (Linnhoff and Flower, 1978). The problem table shows all the sub networks, with the respective heat flows. The 'pinch' was represented by zero heat flow. According to the study presented, exchangers and utility heaters and coolers placed across the pinch are violating the pinch. This violation increases the utility heating and cooling and costs.

For a better visualisation of the exchangers, utilities, steam data and 'pinch' a Grid Diagram is required (Linnhoff & Flower, 1978). This representation allows easy manipulation of matches. A grid diagram is represented below.

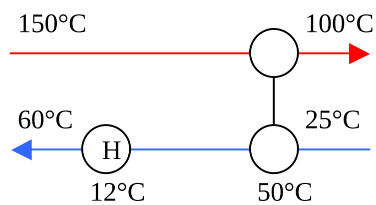

Figure 4.2 - Grid diagram of a process with one heat exchanger and one hot utility.

4.2. Capital, Energy Trade-offs

The capital costs depend on the number of units, heat exchanger area, number of shells, material of construction, equipment type and pressure rating.

Linnhoff *et al.* (1979) explained the equation 4.1 from the Euler's general network theorem. This equation is used for calculation of the minimum number of units. In the earlier stage the equation was presented similar to the one below.

$$U_{units}=N-1 \tag{4.1}$$

Where,

U_{units} is the number of matches or units

N number of streams including utilities

$$N_{units}=S-1 \tag{4.2}$$

Later, the expression 4.1 took the form above. In this expression N_{units} is equal to U_{units} and S is equal to N.

Or, using the next one, when a pinch exists in the problem:

$$N_{units}=(S_{above\ pinch}-1)+(S_{below\ pinch}-1) \tag{4.3}$$

In a composite curve, the relative position of the hot and cold streams represent the best possible counter-current arrangement, *i e*., the available ΔT is maximised and the area for the complete network is minimised. According to Townsend and Linnhoff (1984) the affirmation stated before, is only possible if the matches have the same U (overall heat transfer coefficient) value. However not all the matches have the same value, and so, following the idea of the authors presented above an average U ($\overline{U}$) can be taken for the calculation of the minimum total network area.

$$A_{TOT} = \frac{1}{\overline{U}} \sum_{j} \left(\frac{Q_j}{\Delta T_{LM_j}} \right) \tag{4.4}$$

Where,

j is the counter current sections of the composite curves

Q_j is the section j stream population k

ΔT_{LM_j} is the logarithmic variation of the temperature in section j

$\overline{U}$ is the average of the overall heat transfer coefficient for the matches

In practice, the U values for each match have considerable variation and the average value of U is not possible to be considered. To overcome this problem, Townsend and Linnhoff (1984) presented a new equation for the determination of the minimum total network area (4.5).

$$A_{TOT} = \sum_{j} \frac{1}{\Delta T_{LM_j}} \left(\sum_{k} \frac{|q_k|}{h_k} \right) j \tag{4.5}$$

Where,

j is the counter current sections of the composite curves

ΔT_{LM_j} is the logarithmic variation of temperature in section j

q_k are individual stream heat loads

h_k are the individual stream loads ‘film and fouling’ coefficients

According to Townsend and Linnhoff (1984) the energy, number of units and area targets present trade-offs between them. These tradeoffs can be overcome and optimised in the design stage. However, the tradeoffs only have meaning when equation 4.5 is considered.

4.3. Retrofit

The design of a new system involves the identification of a less expensive network, relative to annualised costs and at the same time guaranteeing operability and safety. However, in a retrofit it is necessary to decrease the consumption of energy used by the existing plant and upgrade the throughput, taking into account that the costs should be the minimum possible (Linnhoff & Tjoe, 1985).

According to Linnhoff & Tjoe (1985) the addition of exchangers to the existing plant is a normal procedure. These new heat exchangers contribute to the efficiency of the network or can improve the efficiency of existing units.

The method implanted by Linnhoff & Flower (1978), of creating Heat Exchanger Networks and setting targets for energy consumption for a given ΔT_{min}, is a starting point for retrofit situations. According to Linnhoff & Tjoe (1985) a repeated targeting using different values of ΔT_{min}, can produce a graph of surface area targets against energy targets, similar to the one below.

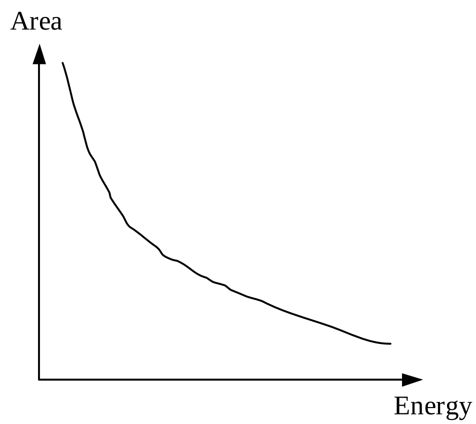

Figure 4.3 - Plot of surface area against energy.

The extreme ends of the plot are also extreme values of ΔT_{min}. In other words, for a small ΔT_{min}, the surface area is large and the energy is low. The opposite is also true. For a large ΔT_{min} the surface area is small and the energy is high.

Also in agreement with this technique (Linnhoff and Tjoe, 1985), it is possible to identify how far away from the optimum, the existing network is. The approximation of the existing network to the optimal can be achieved with the installation of the new heat exchangers and preservation of the existing exchangers.

The 'Surface Area Efficiency' (Linnhoff & Tjoe, 1985) was used to identify how far the existing surface area was relatively to the target area and to calculate the average and marginal payback.

For the use of a retrofit, Linnhoff & Tjoe (1985) proposed two design methods, That were based on the identification of the ΔT_{min} at the targeting stage. One of the methods considered the retrofit design is a grass root design. This first method involved the creation of new MER designs with no heat transfer across the pinch. The most similar networks to the existing networks were selected and evolved. The other method evolved from the existing network. This method started with the identification of the heat exchangers that were crossing the pinch: followed by the selection, removal and reconnection of the heat exchangers. The last step in this method was the capital and payback determination.

A new method for retrofit design combined the thermodynamic analysis of heat exchangers networks and mathematical programming techniques. This method was proposed by Asante & Zhu (1996). The concept of 'pinch match' was introduced with this new method and consists in an exchanger match that determines how close hot and cold streams is closer to a limit value as the heat recovery in the HEN increases. The 'pinch match' determines the placement of the network 'pinch'. This new method also brought a new retrofit algorithm, which is divided into two parts. One was the diagnosis stage that was used for the identification and selection of optimal topology modifications. The other was used to optimise the selected HEN and produce the final retrofit design.

Later Asante and Zhu (1999) introduced a new stage called evaluation stage and created a more specific optimisation stage called cost optimisation stage. This method had the same basis as the one created before by the same authors.

4.4. Methodologies used in the Pulp and Paper Industry

The reduction of energy and water consumption in pulp and paper mills has been deeply studied by several authors, like Wising (2003), Wising *et al.* (2002), Savulescu *et al.* (2000), Bengtsson *et al.* (2002), Edelmann (1999) and Franck *et al.* (1999), Cripps (2000), Ashton *et al*. (1986), Boháček *et al*. (1996).

The different Authors presented above used also different technologies to achieve the same objective. The technologies were all based on the same concept, Process Integration.

In 1986, Ashton *et al*. presented a novel technique in the analysis of the pulp and paper industries. These authors develop an algorithm based on pinch analysis but applicable to pulp and paper industries. However, a few years later Boháček *et al.* (1996) a methodology of Total Site Analysis based on the extension of Pinch Analysis was developed. The modification suggested in this study leads to savings in the natural gas and the related reductions of CO_2 and NO_x and better utilisation of the energy produced.

According to Edelmann (1999) a closed water circulation can reduce the water consumption in a pulp and paper mill. The treatment and reuse of the water may be a reason for the lessened. The closed water cycle was studied using simulation and Pinch Analysis. It was shown by this Author that the complete closure of the water is possible using waste-heat operative multiple effect evaporating for the treatment of the water. The organic contaminants combustion and the bark drying increased the power production. From another point of view, Savulescu *et al.* (2000) defends that the water and energy consumption should be studied at the same time and moreover an analysis of the aqueous effluent system should be done. The objective of this paper was achieving steam savings and reduction of discharged aqueous effluent.

The closure of the water loops produces an accumulation of the Non Process Elements, which need to be removed according to Wising *et al.* (2002). The process to remove NPE is called kidneys. In this paper the kidneys evaluated were pre-evaporation of the effluents, chip pre treatment, and combinations of both. This has a significant impact in the energy demand. This Author proves that the closure of the mill is possible without an increasing in the steam demand.

Wising *et al.* (2003) found that the reduction of the hot water consumption, in an existing pulp and paper mill, produces a reduction in the live steam demand and increases the temperature and quality of the excess heat available. However if the pinch violation was removed, the hot water was no longer important for the steam saving. But significant energy savings are possible. Frank *et al.* (1999) also studied an existing mill and compared it to a new design mill. It was proved that energy savings, in the existing mill, are possible using process changes. These Authors also proves that a direct pumping of pulp to the paper machine can also produce energy savings.

Combined of heat and power (CHP) give a further opportunity for energy cost reduction and decreased the CO_2 global emissions, even when PI approach identify small heat recovery opportunities, according to Cripps (2000). This author also presented an accomplish aspect; the reduction of water also reduces the effluent loads. Same of the authors presented above also defended this idea. The technology presented for water savings are: reduction of the water wasted by better control, rationalisation, and reuse of water. Also a better understanding of the thermal flows and the interaction between water flow rate and heating can produce the saving pretended.

The environmental regulation and new conditions imposed to the pulp and paper industry made it change in terms of technology and requirements. New equipment and the used of new technologies made the environmental impact lessened.

The reduction of carbon emissions is related with the combine production of heat and power (Khrushch *et al.*, 1999). The study presented by these authors focus on the chemical and pulp and paper industries and in both was found potential for CHP and further potential for carbon emissions reduction. According to Martin *et al.* (2000) the recovery of pulp recycling can improve the energy savings and reduce the CO_2 emissions. These authors prove that when a recycling pulp mill is compared with another without the pulp recycling, the first one show benefits in terms of energy and CO_2 emissions.

4.5. Critical Evaluation

The 'Pinch Design Method' (Linnhoff and Hindmarsh, 1982) is an easy method that can be applicable to simple and complex networks. The solution for problems, using this method can be easily found by hand. This method when compared to earlier methods like the TI method (Linnhoff and Flower, 1978) had an advantaged. It could identify stream splitting where is restrict necessary. However when the methods in cause are not well applicable or are very complex, the stream splitting is so clear. The fact that the 'Pinch Design Method' uses the constant CP (Heat capacity flow rate) can be very useful because the problem can be described with a linear relation of temperature enthalpy data.

The 'Pinch Design Method' (Linnhoff and Hindmarsh, 1982) is used to design HENs for all sorts of process. In this particular case (drying) the method created by Linnhoff & Hindmarsh (1982) is used as a starting point for the analysis.

For the retrofit application several methods were presented. Same of them with the use of mathematical programming like the method proposed by Asante & Zhu (1996). This kind of methods can be very helpful in small problems but in more complex processes it may become very difficult to solve.

The method proposed by Linnhoff & Tjoe (1985) can set targets easily and the optimisation of a determined HEN is done based on payback and costs. This method was tested and used in simple and complex processes. This also permits an optimisation step to ensure the operability of the changed process.

All the methods presented before have been largely used in pulp and paper processes. In these kinds of mills the water and heat consumption is very high. The retrofit methods may propose changes in the processes that may bring the consumption to lower levels. The different processes in a pulp and paper mill are very complex and the translation in mathematical program can be very difficult. This fact may explain the inadequacy of the method proposed by Asante and Zhu (1996).

The retrofit method proposed by Linnhoff and Tjoe (1985) was based on the identification of ΔT_{min} at targeting stage. The identification of targets in pulp mills is very complicated whish makes the ΔT_{min} of difficult access. The surface area efficiency (Linnhoff and Tjoe, 1985) can be very useful in the determination of the difference between the existing and the target surface area efficiency.

The application of the pinch analysis was a constant in all the studies and thesis about pulp and paper industries presented. This methodology was used as a tool in energy and water. Also the objective of the several paper presented is similar among them. They all have as objective the water and energy reduction. Nowadays the environment restrictions are a very important issue especially in the pulp and paper industry.

The different technologies used by the different Authors all lead to the reduction to the energy savings. Same of that studies beguine with an analysis on the water reduction by closing the water circulation (Edelmann, 1999, or Savulescu *et al.*, 2000, etc) and consequent reduction of energy and environment impact. However, Authors like Frank *et al.* (1999) study an existing mill apparently very energy efficient but with an opportunity for energy savings.

5. Methodology

Understanding all the processes that are present in pulp production is a very important. In this particular case the understanding in terms of energy consumed for each stage in the process makes a difference in the first decision. The following table shows the energy consumed for each stage.

Table 5.1- Energy consumption for each stage in the production of pulp.

		Steam consumption (kW)	Steam consumption (%)
Fiber line	Wood Handling	0.00	0.00
	Continuous Cooking	36065.40	23.55
	Brown Stock Washing	0.00	0.00
	Bleaching	10442.90	6.82
	Drying	44323.96	28.94
Chemical Recovery	Evaporation	58682.94	38.32
	Causticizing and Lime Reburning	343.80	0.22
Chemical Products		3295.20	2.15

The table 5.1 identifies the two most energy consuming stages i e., evaporation and drying. Evaporation requires almost 10 % more energy, which makes it a good stage for a study of steam savings however, as was said before, evaporation cannot be redesigned, and for this reason any proposal of changes will not be taken into account by PORTUCEL.

Therefore the drying stage was chosen, considering that is the second most energy consuming stage (approximately 29 % of the global steam consumption) and could be consuming an excess of energy.

The resume of all steps of the methodology is presented in figure 5.1. The possibility of improvement begins with the use of the pinch design method, which method in this study is considered as the starting point for a retrofit.

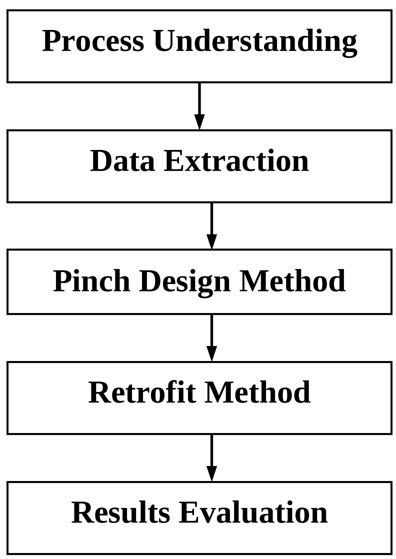

Figure 5.1- Methodology steps.

5.1. Data Extraction

Utility streams identification is an important issue in the data extraction part. Data extraction determines in certain ways the solution of this study. Generally in the Pulp and Paper industry, stream data definition is not simple.

For the thermal data extraction it was necessary to supply target and enthalpy temperature of all the streams in the process. For example, in one of the heat exchangers, like the one presented below:

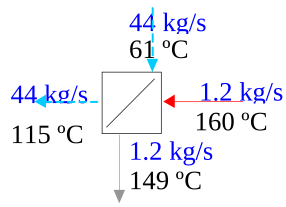

Figure 5.2- Heat exchanger present in the drying process (Martins & Barata, 2003).

The supplied temperature of the air stream was 61 ºC and the target temperature was 115 ºC (break line). The other stream in Figure 5.2 was the utility. In this case the utility was low pressure steam II (LPS II), which was supplied at 160 ºC and its target temperature was 149 ºC.

In the case of the thermal data extraction of the *devron*, the heating source considered was a hot utility:

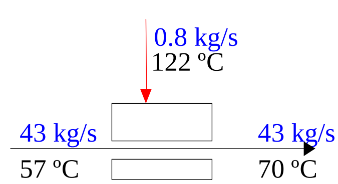

Figure 5.3- *Devron* presented in the drying process (Martins & Barata, 2003).

The pulp was considered as a cold stream. The supplied temperature was 57 ºC and the target temperature was 70 ºC.

The dryer was divided into three groups of cylinders. The second and the third are considered together and are represented in figure 5.4. Steam is considered as a hot utility and the air inside the dryer enclosure is not considered as a heat source to the pulp. The same consideration is given to the first group of cylinders in the dryer.

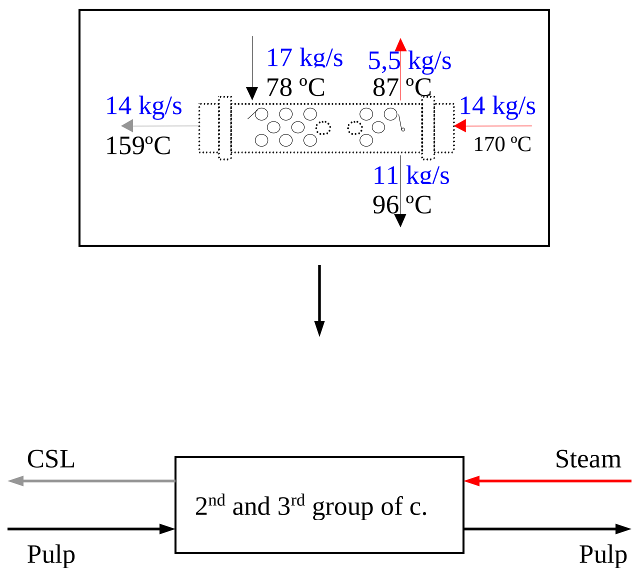

Figure 5.4- Dryer second and third group of cylinders.

Table 5.2 shows the data extracted from the drying stage flow sheet.

Table 5.2- Streams extracted from the flow sheet.

Number	Name	Ts (ºC)	Tt (ºC)	ΔH (kW)	CP (kW/ºC)	HTC (kW/m^{2}ºC)
1-HU	Steam *devron*	122	68	2368.90	43.87	0.375
2-HU	Steam dryer 1	141	141	11760.5	117605.00	0.07
3-HU	LPS I dryer 2	170	159	26698.014	2427.09	0.07
4	Air heat 1	109	70	8565.52	219.63	0.03
5-HU	LPSII 2	160	149	3373.54	306.69	0.17
6-HU	LPSI 3	170	161	508.28	56.48	0.17
7	CSL	135	104	3369.08	108.68	1.15
8	Pulp *devron*	57	70	1967.68	151.36	0.375
9	Pulp dryer 1	65	78	114.14	8.78	0.05
10	Pulp dryer 2	78	96	413.30	22.96	0.05
11	Air in 1	23	61	3132.00	82.42	0.03
12	Air in 2	61	115	3186.00	59.00	0.17
13	Air in 3	59	92	360.00	10.91	0.17
14-CU	Water	40	71	3369.08	108.68	1.15

However, as was explained in the Process Description (Chapter 2), the Drying stage involves three pre-heaters and three heat exchangers. The function of these units is to heat up atmospheric air. The streams used to represent this fact are highlighted (Streams 6, 7, 13 and 14) in the table above. For a correct representation of all three pre-heaters and heat exchangers it is necessary to split the highlighted streams. This represented in figure 5.5.

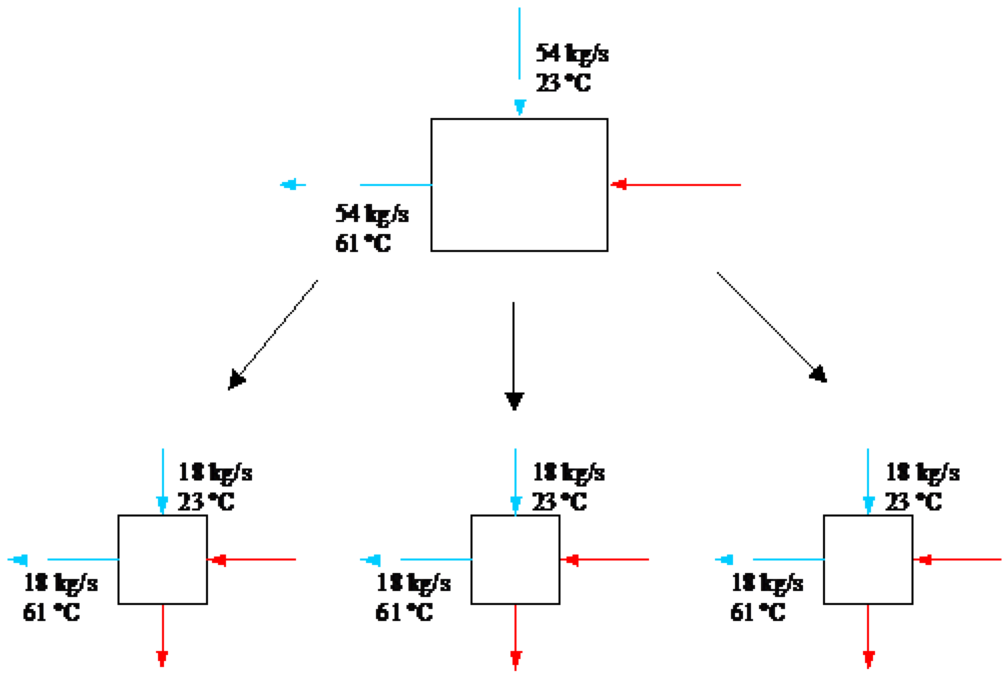

Figure 5.5- Heat exchangers (pre-heaters) representation.

The same assumption is taken for the second heat exchangers. In the table below are shown all the streams with all the assumptions considered.

Table 5.3 - Existing streams in the flow sheet.

Number	Name	Ts (ºC)	Tt (ºC)	ΔH (kW)	CP (kW/ºC)	HTC ($kW/m^{2o}C$)
1-HU	Steam *devron*	122	68	2368.90	43.87	0.375
2-HU	Steam dryer 1	141	141	11760.50	117605.00	0.07
4-HU	LPS I dryer 2	170	159	26698.01	2427.09	0.07
5	Air heat 1	109	70	2855.17	73.21	0.03
6	Air heat 1	109	70	2855.17	73.21	0.03
7	Air heat 1	109	70	2855.17	73.21	0.03
9-HU	LPSII 2a	160	149	1379.83	125.44	0.17
10-HU	LPSII 2a	160	149	1379.83	125.44	0.17
11-HU	LPSII 2b	160	149	613.88	55.81	0.17
12-HU	LPSI 3	170	161	508.28	56.48	0.17
13	CSL	135	104	3369.08	108.68	1.15
14	Pulp *devron*	57	70	1967.68	151.36	0.375
15	Pulp dryer 1	65	78	114.14	8.78	0.05
16	Pulp dryer 2	78	96	413.30	22.96	0.05
17	Air in 1	23	61	1044.00	27.47	0.03
18	Air in 1	23	61	1044.00	27.47	0.03
19	Air in 1	23	61	1044.00	27.47	0.03
20	Air in 2a	61	115	1062.00	19.67	0.17
21	Air in 2a	61	115	1062.00	19.67	0.17
22	Air in 2b	61	115	472.00	8.74	0.17
23	Air in 3	59	92	360.00	10.91	0.17
22-CU	Water	40	71	3369.08	108.68	1.15

5.2. Economic Data

The economic data was used to calculate capital and operating costs. The capital cost is based on the heat exchanger cost and the operating cost involves the cost of the utilities in the process (hot and cold). The total network cost is the addition of both capital and operational costs.

The hot and cold utility costs were given by PORTUCEL and are presented in the Table 5.3.

Table 5.4- Utility costs in euros and pounds.

Utility	Cost (€/kWh)	Cost (£/kWh)
Steam	150.36	103.75
Water	0.036	0.025

According to Banco de Portugal (2003) the exchange rate was 0.69 Pounds to 1 Euro.

The heat exchanger used in this process is a shell and tube type. The heat exchanger cost estimation was based in Hall method (Tall *et al.*, 2003). The Hall correlations are a derivation of the Poruhit method. He developed five correlations, however in this case only one is used.

Carbon steel $7000 + 360.A^{0.80}$ (5.1)

This correlation data is from the year 1982. A correlation for the current year 2003 is:

Carbon steel $7252 + 372.96.A^{0.912}$ (5.2)

This correlation was obtained considering an inflation of 3.6 % (Banco de Portugal, 2003).

6. Results

6.1. Existing Process

As it was described in Methodology (Chapter 5) this study started with an analysis of the existing drying process.

The Composite curve for the existing process is presented below.

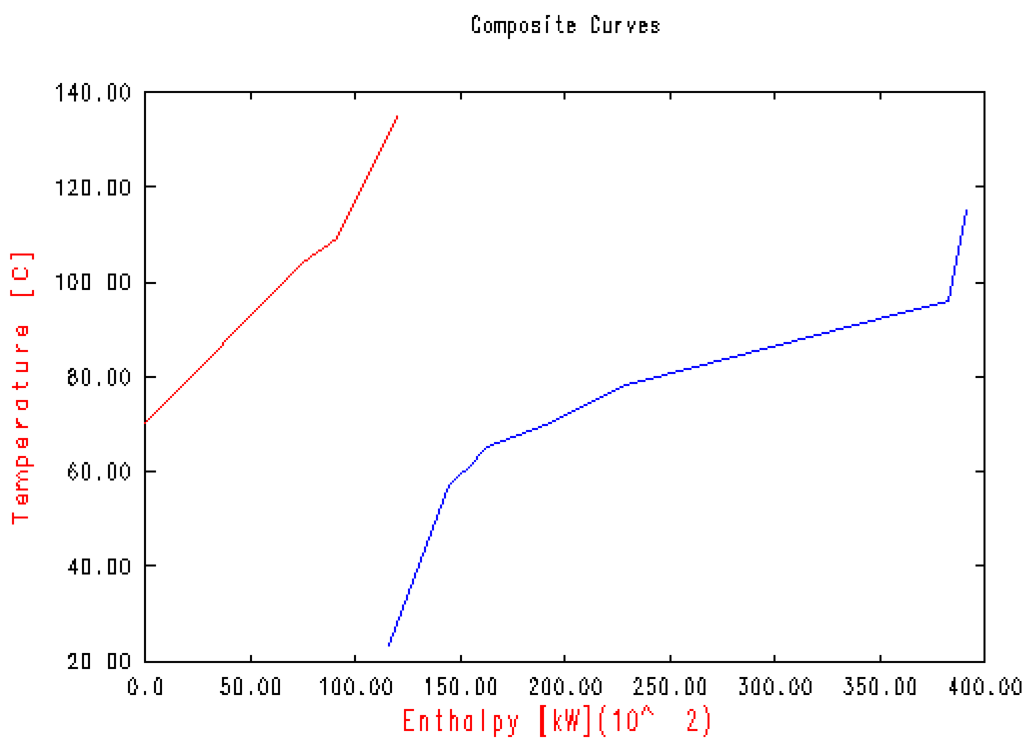

Figure 6.1- Composite Curves for the existing process.

For the presented composite curve the data was extracted as was explained in the Methodology.

The recovery temperature approach for the existing process was 11 ºC. According to the composite curve (figure 6.1) the minimum hot utility requirement was 27 208.20 kW.

The calculated utility for the process, according to the data supplied by PORTUCEL, was 44 709.23 kW. Comparing the existing utility in the process with the minimum utility required, it was possible to evaluate the excess heat existing at this stage (2.5 GJ/ADt).

The heat exchangers profile is showed below.

Table 6.1 - Heat exchangers profile.

Heat exchanger number	Hot Streams temperature (ºC)		Cold steams temperature (ºC)		Duty (kW)	Area (m^2)
	Ts	Tt	Ts	Tt		
1	122	68	57	70	1967.68	397.59
2	141	141	65	78	5195.86	2572.48
3	170	159	78	96	14282.70	6322.91
4	109	94.74	23	61	1044.00	841.52
5	109	94.74	23	61	1044.00	841.52
6	109	94.74	23	61	1044.00	841.52
7	160	149	61	115	1062.00	194.87
8	160	149	61	115	1062.00	194.87
9	160	149	61	115	472.00	86.61
10	170	161	59	92	360.00	47.34
11	135	104	40	71	3369.08	91.55

The Heat Exchanger Network for the existing process, considering the data presented before, is showed below (figure 6.2).

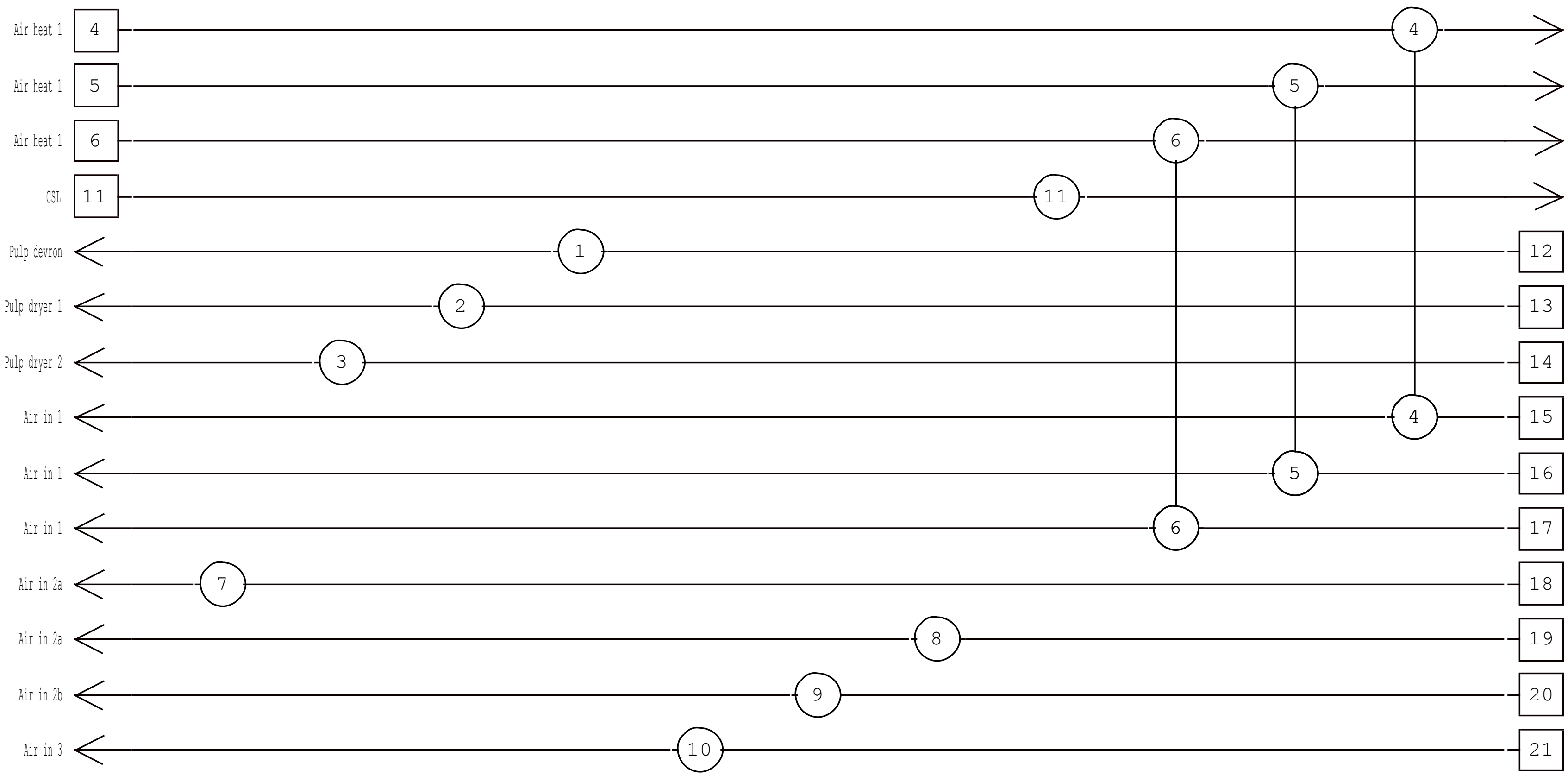

Figure 6.2- Existing network.

6.2. Retrofit

6.2.1. Surface Area Efficiency

Linnhoff and Tjoe (1985) introduced, in the study of a retrofit, the concept of *Surface Area Efficiency*. Surface area efficiency can be obtained from the existing area and the target area. It is denominated α,

$$\alpha = \frac{Area_{target}}{Area_{existing}} \tag{6.1}$$

This value determines how close the existing surface area is to the target surface area.

As an assumption, α can be considered constant. However, in practice, α is expected to improve as the scoop for energy savings increase. In cases where α is close to the unit (one), the assumption of constant α can be used.

In the Figure 6.3, presented below, it is possible to see that the existing area was very close to the target area.

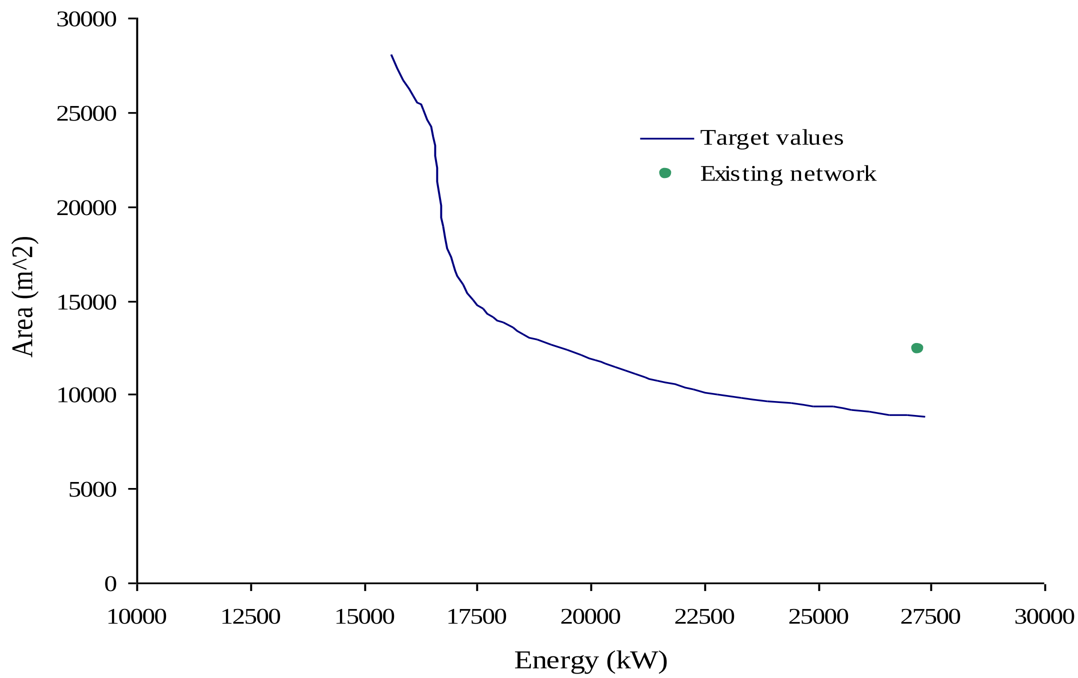

Figure 6.3- Energy-area plot for the drying process.

It is possible to identify the slight difference between the ideal area and the existing area at the same target energy. The point above the curve represents the existing network.

At the same target energy (27 208.20 kW) the ideal target area is 8 986 m^2 and the existing network area is 12 432.80 m^2. In this case the *Surface Area Efficiency* (Linnhoff and Tjoe, 1985) is calculated as explained above and its value is 0.72.

6.2.2. Capital Investment for Energy Savings

The area efficiency calculated before was very close to the unit and so the assumption of constant α (area efficiency) could be assumed.

According to Linnhoff and Tjoe (1985) large energy savings required also large capital investment, long payback and a small value of ΔT_{min}.

The capital investment was calculated using the equation below (Azmi, 2001)

$$Investment = \Delta N \left(a + b \left(\frac{\Delta A}{\Delta N} \right)^{C} \right) \tag{6.2}$$

In this equation ΔA is the additional area required; ΔN is the ratio between the additional area required and the average size of exchanger's shells. The coefficients represented by a, b and c are equal to the coefficients used in the heat exchanger law presented before.

In this case the investment cost was:

$$Investment = \Delta N \left(7252 + 372.96 \left(\frac{\Delta A}{\Delta N} \right)^{0.912} \right) \tag{6.3}$$

The average size of the heat exchanger was calculated assuming one shell per heat exchanger. The number of heat exchangers in the existing heat exchanger network was 11 and the total area was 12 432.80 m^2. The size of the heat exchangers was not constant and for this reason was considered 4 groups of heat exchangers with approximately the same size.

Table 6.2- Average shell area for different ranges of heat exchangers sizes.

Heat exchanger Size range (m^2)	Number of heat exchangers	Total area (m^2)	Shell area per heat exchanger (m^2)
30≤A≤100	3	225.5	75.17
100≤A≤500	3	787.33	262.44
500≤A≤1000	3	2524.55	841.52
1000≤A	2	8895.39	4447.70

The average size of the heat exchanger shell was 511.53 m^2.

The additional area required (ΔA) was calculated for constant surface area efficiency and for incremental surface area efficiency. The additional area required for incremental area efficiency was calculated using a simple substation between the target area at different ΔT_{min} and the existing area. An example is presented below:

For ΔT_{min} =24 °C ⟹ Target area = 28 080 m^2

ΔA = 28 080.00 - 12 432.80 = 15 647.20 m^2

For constant surface area efficiency the incremental area was calculated dividing the substation between the target area at different ΔT_{min} and the existing area by α, like the example presented below:

For ΔT_{min} =24 °C ⟹ Target area = 28 080 m^2

ΔA = (28 080.00 - 12 432.80) / 0.72 = 21 649.07 m^2

In the Figure 6.4 is represented the capital investment against energy savings when the area efficiency is constant and when the area efficiency is incremental. From the same figure it is also possible to see that both curves are close. The difference between the curves is because of the surface area efficiency that is equal to 0.72.

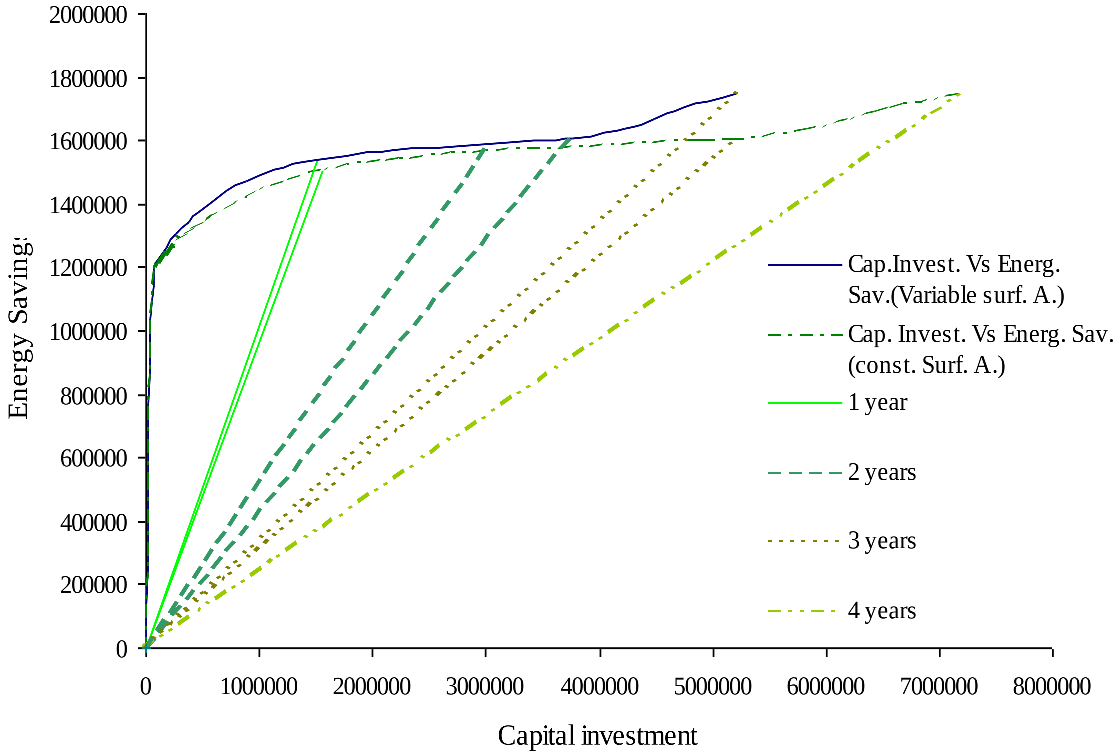

Figure 6.4- Capital investment (€) against energy savings (€/y).

The straight lines represent the payback time in years. Each line is represented twice, one for the increment, the other for the constant surface area efficiency. The table below shows the capital investment and energy savings for the different payback times and curves.

Table 6.3- Capital investment and energy savings corresponding to different paybacks.

	Incremental Surface Area Efficiency				
ΔT	Target energy (kW)	Target area (m^2)	Capital Investment (€)	Energy savings (€/y)	Payback time (years)
24	15 600	28 080	5 196 806	1 745 436	3
30	16 530	23 750	3 758 710	1 605 599	2
32	16 970	16 970	1 506 912	1 539 439	1
Constant Surface Area Efficiency					
24	15 600	28 080	7 190 168	1 745 436	4
30	16 530	23 750	5 200 455	1 605 599	3
31	16 750	18 990	3 013 150	1 572 519	2
33	17 190	15 830	1 561 704	1 506 360	1

Considering incremental Surface area efficiency and a payback time of one year, the retrofit design can be obtained.

6.2.3. Retrofit Design

The retrofit design can be obtain using cross-pinch method. This method is based on finding the heat exchangers that are transferring heat across the pinch, remove and reconnect matches.

Considering a payback time of one year for incremental surface area efficiency, the ΔT is 32 °C and the correspondent pinch temperature is 73.50 °C. Taken into account the existing network, the number of heat exchangers that cross the pinch are three (4, 5, 6) and one utility (11).

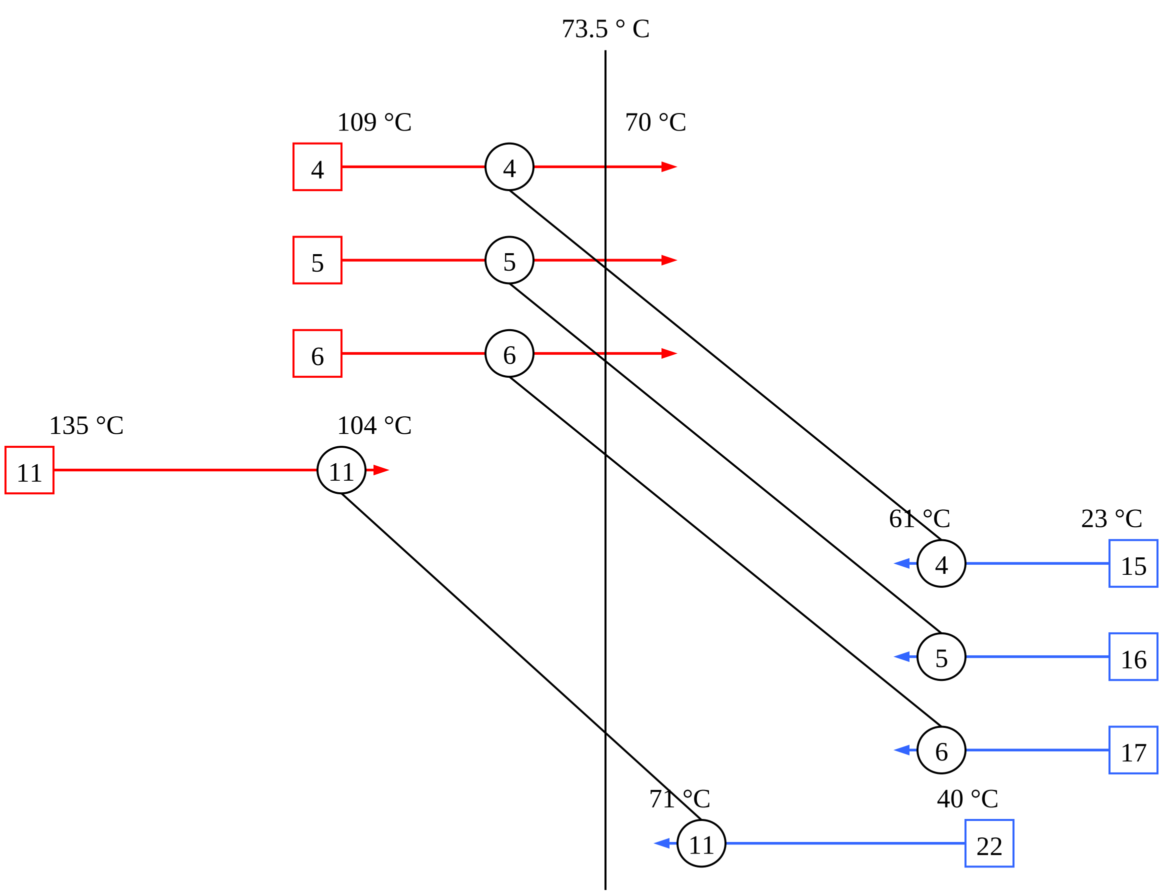

Figure 6.5- Schematic representation of the cross-pinch heat exchangers.

For a payback of two years with the same considerations used before, the schematic representation presented in figure 6.5 is also valid. In this case ΔT is equal to 30 °C and the pinch is at 72 °C.

The heat exchanger network after the reconnection of the matches is presented in Figure 6.6. The hot utility used, according to the network report, was 20 890.6 kW, however the minimum hot utility required is the same as for the existing network (27 208.20 kW).

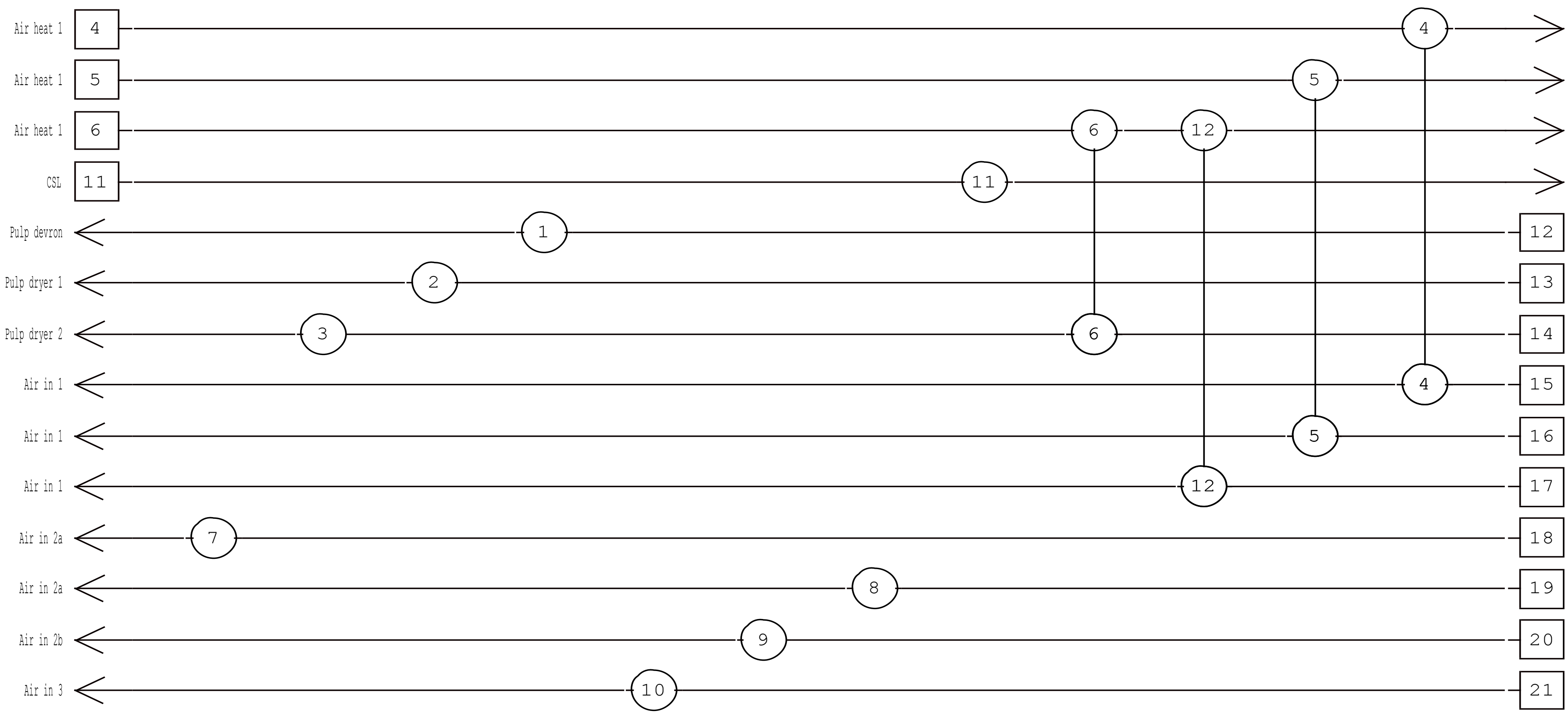

Figure 6.6- Heat exchanger network after reconnection.

The area for the retrofit design was 14 994.2 m^2. This new network requires two new heat exchangers and more two shells, one for each heat exchanger (was considered before that each heat exchangers has only one shell). Three exchangers were crossing the pinch, however the reconnection was successful for only one. The small number of streams that go from one side of the network to the other side is the reason of the unviable reconnection of the other two exchangers. The capital investment, after design, is 1 506 912 € for an annual saving of 1 539 439 €/y. The payback period is one year.

The report of the retrofit design is shown in figure 6.7.

Figure 6.7- Retrofit design report (SPRINT, 2003)

```
Hot Uty  :  20890.6     [kW]       Hot Uty Cost  : 0.161209E+07 [£/yr]
Cold Uty :  3369.08     [kW]       Cold Uty Cost :  84.2270     [£/yr]
Units    :       12     [N]        Utility Cost  : 0.161217E+07 [£/yr]
Area     :  15356.7     [m^2]      Area Cost     : 0.000000E+00 [£/yr]
                              Total Network Cost  : 0.161217E+07 [£/yr]

Total area   :  15356.7     [m^2]
Process area :  6974.37     [m^2]
Utility area :  8382.35     [m^2]
Capital Annualisation Factor :      1.0240
Minimum DT Approach        7.78 [C]

 Retrofit Information
 Existing Energy
 Hot Uty:  44709.2     [kW]       Hot Uty Cost  : 0.317266E+07 [£/yr]
 Cold Uty:  3369.08     [kW]       Cold Uty Cost :  84.2270     [£/yr]
 Energy differences
Hot Uty:  23818.7     [kW]       Hot Uty Saving : 0.156057E+07 [£/yr]
Cold Uty : 0.000000E+00 [kW]       Cold Uty Saving: 0.000000E+00 [£/yr]
Total Savings    : 0.156057E+07 [£/yr]
Total Investment : 0.000000E+00 [£]
```

Payback (yr) : 0.000000E+00 [yr]

	Total	Process	Utility	
Installed area :	14994.2	6715.19	8279.02	[m^2]
Installed area used :	14994.2	6715.19	8279.02	[m^2]
New area required :	362.518	259.184	103.334	[m^2]

Exch No.	Area [m^2]	1-2 Sh. [N]	Duty [kW]	Cap. Cost [£/yr]	Uty. Cost [£/yr]
1hu Added	60.2196	0	140.030	0.000000E+00	
1hu Exist	397.590	1	1827.65	0.000000E+00	
2hu Added	0.494164E-01	0	0.109397	0.000000E+00	
2hu Exist	1619.98	1	3384.58	0.000000E+00	
3hu Added	27.9612	0	64.3009	0.000000E+00	0.130540E+07
3hu Exist	5646.21	1	12517.9	0.000000E+00	
4 Added	21.2790	0	31.8952	0.000000E+00	
4 Exist	841.520	1	1012.10	0.000000E+00	
5 Added	21.2790	0	31.8952	0.000000E+00	
5 Exist	841.520	1	1012.10	0.000000E+00	
6 Added	121.146	0	28.0973	0.000000E+00	
6 Exist	3624.98	1	1671.90	0.000000E+00	
7hu Added	4.66038	0	34.5816	0.000000E+00	110183.
7hu Exist	194.870	1	1027.42	0.000000E+00	
8hu Added	4.66038	0	34.5816	0.000000E+00	110183.
8hu Exist	194.870	1	1027.42	0.000000E+00	
9hu Added	2.07033	0	15.3626	0.000000E+00	48970.0
9hu Exist	86.6100	1	456.637	0.000000E+00	
10hu Added	0.292338	0	2.53247	0.000000E+00	37350.0
10hu Exist	47.3400	1	357.468	0.000000E+00	
11cu Added	3.42054	0	125.876	0.000000E+00	84.2270
11cu Exist	91.5500	1	3243.20	0.000000E+00	
12 Added	95.4801	0	95.0992	0.000000E+00	
12 Exist	1407.17	1	948.901	0.000000E+00	
12	15356.7	12		0.000000E+00	0.161217E+07

6.3. Network Pinch method

The network pinch is the pinch caused by one or more heat exchangers and is achieved when the maximum heat recovery of the structure equals the maximum heat recovery of the process. The limit for the heat recovery achieved by the heat exchanger network is the pinch match. The pinch match identifies the bottleneck in the network.

The pinch network limits the existing network, however it can be overcome by applying topologic changes in the heat exchanger network. The changes are resequencing, inserting a new match and stream splitting. Resequencing is the movement of a match from below to above the pinch. Inserting a new match is the introduction of a new exchanger that transfers heat from below to above the pinch. Stream splitting is, as the name identifies, the splitting of one or more streams in the existing network with the same objective of the others presented before.

SPRINT (2003) was used as a tool to perform the network pinch analysis and to overcome the network pinch, using resequencing, piping and addition of a new exchanger.

According to the network pinch report there is one pinched exchanger for a minimum approach temperature of 11 °C and a pinched network hot utility of 24 402.20 kW. However, when the pinch network has to be overcome using resequencing, piping or addition of new heat exchangers, the analysis are abandoned because there are no loops or paths.

6.4. Proposed Modifications Evaluation

The ideas and modifications presented in this study are in this chapter, applicable to the PORTUCEL pulp production. The aim of these modifications is the reduction in steam and water requirements in an environmentally friendly way.

6.4.1. Case 1: Reuse of the moister air

The hot moist air from the pulp dryer is used to heat atmospheric air. The most air contains approximately 7.5 kg/s of water. Considering that the condensation of the water vapour is possible without losses, it can be used in the boiler feed water tank. The water consumption at the recovery boiler stage is 103 kg/s (6 t/ADt) and the steam consumption by direct injection is 3.7 kg/s (0.22 t/ADt) that makes a total mass flow of approximately 107 kg/s (6.2 t/ADt). The addition of 7.5 kg/s of water reduces the boiler feed water by the same amount. Reduction of water at this stage is approximately 7 %. However, the overall reduction in the water consumption is not significant.

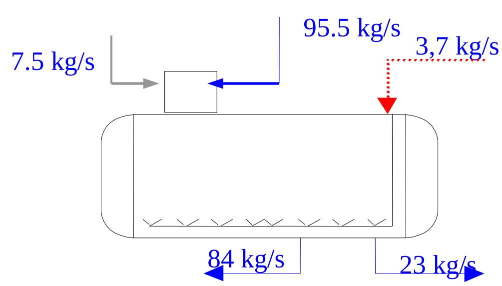

Figure 6.8- Boiler feed water tank with the propose modification.

6.4.2. Case 2: Reuse of the condensate steam

The condensate formed in the upper, lower circulation heat exchangers and washing circulation heat exchangers at the continuous cooking stage can be used at the drying stage to heat the air instead of being stored in the condensate collector. The amount of condensate formed is approximately 11.2 kg/s and the amount of steam used is approximately 1.2 kg/s (0.07 t/ADt).

Table 6.4- Heat exchanger conditions.

	Condensate		Air	
Temperature (°C)	183.5	120	61	115
Mass flow (kg/s)	11.2		44	
Enthalpy (kW)	2972.86		2596	

The use of condensate reduces the LPS II consumption at this stage in 7.5 %.

The investment is 28 363 € and savings are 711 093 €/y.

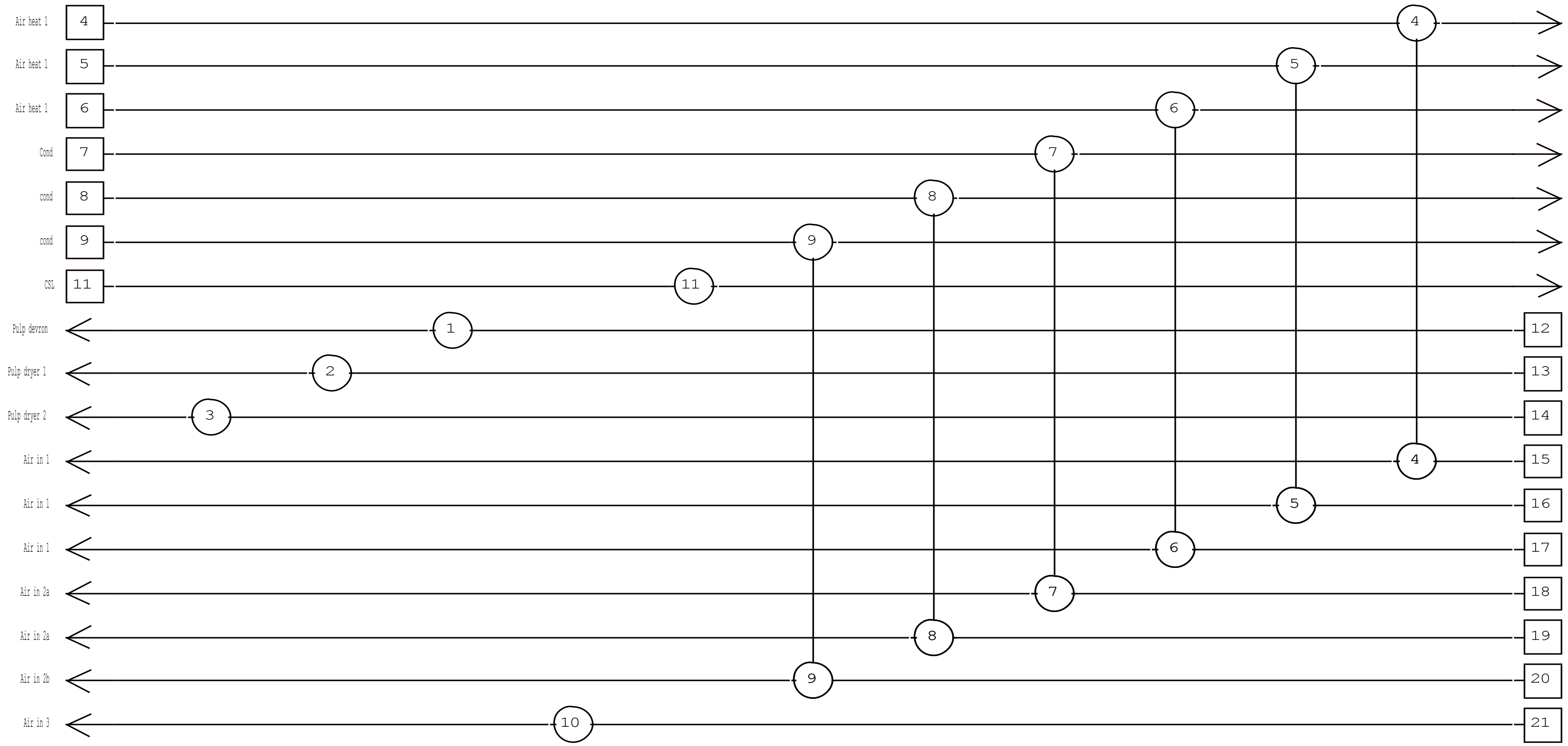

Figure 6.9- Heat exchanger network for case 2.

6.4.3. Case 3: New dryer

The installation of a new dryer has been studied by several authors as a possibility for improvement at the dryer stage and consequently in the production of pulp.

The installation, of a new dryer was evaluated by Wising *et al*. (2002). This evaluation is made in a theoretical way and based on previous studies. The costs of a secondary heat system and new dryer have to be considered. The disposal of one or two dryer existing at the dryer stage has also to be taken is account. The investment in this case is large and the payback time long. This makes case 3 not economic feasible.

6.5. Summary of the results

A reduction in the hot utility (steam used) permits the utilization of that excess at another stage in the pulp mill.

Table 6.5- Resume of the results obtained.

	Number of heat exchanger units	Min. Hot utility required (kW)	Area (m^2)
Existing design	11	27 208.20	12 432.80
Retrofit design	12	27 208.20	15 356.70
Case 2	11	22 479.08	12 347.40

From the table 6.5 it is possible to see that the retrofit design and the existing design required the same minimum hot utility, however the steam used was less (20 890.60 kW). This means that the excess of steam available to be used in another stage in the pulp production increase.

Case 3 is not mentioned in the table 6.5 or table 6.6. This case was theoretically considered due to the reasons presented before. This case requires a total redesign of the drying process. Steam savings are not possible to quantify however Capital investment is certainly high.

The capital investments and annual savings are presented below.

Table 6.6- Results summary for Capital investment (€) and annual savings (€/y).

	Capital investment (€)	Annual savings (€/y)
Retrofit design	1 506 912	1 539 439
Case 2	28 363	711 093

The annual savings for the retrofit design are larger than the annual savings in case 2, however the investment is also larger.

7. Discussion

The objective of this work is the reduction of water and steam consumption in PORTUCEL pulp mill. The problem is addressed in a theoretical and technical way. Water reduction is a very important issue throughout this work. However, the water circulation in PORTUCEL is very complex. Steam reduction is, in this work, studied more technically with respect to the drying stage and the impact in the overall consumption.

It is important to understand that in some way, water reduction is connected with steam reduction. A reduction in water will cause a reduction in the amount of steam used to heat it. In PORTUCEL, warm and hot water necessary to the different stages is heated using steam and condensate produced in each stage, which limits the possibility of water reduction. A reduction, which would result in a reduction in wastewater flow and consequently a reduction in cost for wastewater treatment.

Excess heat at the drying stage was first used to remove the pinch violations. In this case the reconnection of the heat exchangers was not successfully done for all of them due to practical constrains. Even obeying to constraints, the new design was economically beneficial.

The substitution of the dryer by another type of dryer was theoretically considered. The modification of the cylinder dryer did not seem economical beneficial. The cost of the installation and the dryer would be very high with a very long payback time. For a more detailed study, a simulation and optimisation was required.

The CO_2 emissions reduction and the wastewater effluents should be determined for each modification. Also the impact of using the excess heat in the emission and wffluents should be quantified.

8. Conclusion

Pulp mills are very energy and water intensive industries. Nowadays environmental restrictions are imposing limits on emission and effluent pollution that makes steam and water reduction an important issue.

In PORTUCEL the steam and water consumption is higher than in the model mills presented in the Literature Review. From the pulp process analysis it was possible to identify that the evaporation stage was the most energy consuming process. It consumes 38.32 % of the global steam production. However, this stage is not possible to redesign. The second most energy consuming process is drying, which makes it a good stage to study steam savings.

The analysis to the drying process identifies an excess of heat of 2.5 GJ/ADt. The possibility to use the excess heat in removing the pinch violation was used. However, due to practical constraints, all the violations could not be removed. The retrofit design for a payback of one year has a capital investment of 1 506 912 € and 1 539 439 €/y as annual savings.

From another perspective, the excess heat found in the drying process could be used at the evaporation II stage, reducing in this way the LPS (low pressure steam) consumed and at the continuous cooking stage reducing the MPS (medium pressure steam) consumed.

Case 2, where condensate was reused in the drying process, was the case with the lowest investment (28 363 €) and also with the lowest annual savings (711 093 €/y). This modification lead to a reduction in the steam consumed by the drying stage of approximately 4 %.

Case 3, implied a dryer machine modification, was only proposed theoretically. Considering previous studies, the investment is very high and the steam savings are not significant.

The reduction of water was slightly addressed in case 1, where the condensation of the moister air is proposed and used at the boiler feed water tank. This modification reduces the water to the tank in approximately 7 %.

9. Suggestions for Further Work

In this work was assumed to exist excess heat at the drying stage. For a better evaluation of the excess heat existing in the all mill another stages should be studied. Stages like evaporation and continuous cooking should be studied.

The use of the excess heat at stages like evaporation or continuous cooking should be deeply studied and the new design of these two stages simulated and optimised.

Technologic modification, for example type of dryer should be simulated and optimised to obtain quantitative results instead of qualitative. Also a combine heat and power analysis should be done and further modification simulated.

For a better evaluation of the excess water used in the mill, water pinch analysis should be done. And than complementary steam pinch analysis.

The CO_2 emission and effluent reduction from the reduction of steam production and water reduction should be evaluated in a quantitative way, so that the environmental impact could be determined.

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Appendices

Drying process data:

The data presented was provided by PORTUCEL.

In this process are present three parallel heat exchangers that have the function of pre-heating air coming from the atmosphere. In this table is presented the flows of the three heat exchangers.

	Steam from dryer		Air	
	In	Out	In	Out
Temperature (ºC)	72	62	23	61
Mass (kg/s)	61.9		54	
Mass (t/ADt)	3.7		3.2	
Hr (%)	----	----	75	10
h (kJ/kg)			55	113

After the heat exchangers below presented there are more three parallel heat exchangers.

	LPS II		Air	
	In	Out	In	Out
Temperature (ºC)	160	149	61	115
Mass (kg/s)	1.2		44	
Mass (t/ADt)	0.07		2.6	
Cp (kJ/kgºC)	----	4.18	----	----
Hr (%)	----	----	10	1
h (kJ/kg)	2770	----	113	172

Data for the heat exchanger use to heat the air in the dryer pockets.

	LPS I		Air	
	In	Out	In	Out
Temperature (ºC)	170	160	69	115
Mass (kg/s)	0.18		10	
Mass (t/ADt)	0.01		0.6	
Cp (kJ/kgºC)	----	4.18	----	----
Hr (%)	----		10	1
h (kJ/kg)	2782		111	147

Data for the first dryer cylinder group:

	Steam			Paper	
	In	Out		In	Out
Temperature (ºC)	141	141		65	78
Mass (kg/s)	4.9	0.6	4.3	19	17
Mass (t/ADt)	0.29	0.04	0.25	1.1	1.0
Cp (kJ/kgºC)	----	----	4.18	2.69	2.49
Humidity (%)	----	----	----	53	60
h (kJ/kg)	2782	2735	----	----	----

Data for the second and third dryer cylinder group:

	LPS I			Paper	
	In	Out		In	Out
Temperature (ºC)	170	159		78	96
Mass (kg/s)	14	4.6	9.4	16.8	11.3
Mass (t/ADt)	0.81	0.27	0.54	1.0	0.66
Cp (kJ/kgºC)	----	----	4.18	2.49	1.67
Humidity (%)	----	----	----	60	89
h (kJ/kg)	2782	2756	----	----	----

Water heater data:

	Water		CSL	
	In	Out	In	Out
Temperature (ºC)	40	71	135	104
Mass (kg/s)	26		12	
Mass (t/ADt)	1.51		0.7	
Cp (kJ/kgºC)	4.18		4.18	

Devron data:

	LPS I		Air	
	In	Out	In	Out
Temperature (ºC)	122	68	69	115
Mass (kg/s)	0.81		10	
Mass (t/ADt)	0.05		0.6	
Cp (kJ/kgºC)	----	4.18	3.51	3.52
Humidity (%)	----	----	24	23
h (kJ/kg)	2710		----	----