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Base case process development for energy efficiency improvement, application to a Kraft pulping mill. Part I: Definition and characterization☆

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ABSTRACT

The development of a base-case process is a fundamental step in an energy efficiency study to obtain reliable results. However, this step is often overlooked and there are no clear guidelines for the systematic development of the base-case. A methodology has been proposed to properly define and evaluate the complete process for a subsequent in-depth energy analysis. It consists of two stages: definition and characterization of the process, and benchmarking analysis. In this paper, the first stage is presented. The base-case should encompass the process and the utilities systems, i.e., steam and water, as they are the driving forces of the chemical transformations. A four-pronged procedure is proposed to properly define and characterize a process and its utilities: data gathering, master diagram construction, utilities systems analysis, and simulation. The main objective is to build a computer simulation model to provide detailed information on production, distribution, utilization and post-utilization treatment of steam and water. Process inefficiencies are also identified, such as the low condensate recovery or the presence of non-isothermal mixing points. The procedure has been applied to an operating Kraft pulping mill in Eastern Canada.

Keywords: Energy efficiency; Base-case process definition; Utilities systems; Simulation; Kraft process; Energy optimization; Water optimization

1. Introduction

The analysis of the operation of the Kraft process has been the subject of a number of recent studies. Klugman et al. (2007) performed an energy audit in an operating mill with three process lines of different construction period. The audit consisted of identifying all energy and electricity consumers and of comparing the results between the three lines. Energy outputs such as effluents, power generated, steam venting, district heating are also quantified. A detailed description of several elements required for an energy study is shown by Browne (1999). These elements include the identification of steam consumers, efficiency of the equipment, overview of pinch analysis and process simulation, control strategies, and power house operation. Turner (1994) shows several elements required to perform a water audit. These elements include the identification of water consumers, effluents producers, efficiency of the equipment, and reutilization strategies. In these works, some of the aspects required in the development of a base-case process and evaluation of the energy efficiency are highlighted. However, they consider water and energy independently and fail to cast light on the interactions between the different sections of the process and between the steam and water systems. In addition, they do not present a structured approach for the base-case development and for the evaluation of the different elements to be considered in an energy and water study. Several noteworthy studies have come from Scandinavia. Axelsson and Berntsson (2005) performed a pinch analysis in a state of the art-mill. Axelsson et al. (2006) described two typical Scandinavian mills that vary by the level

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of water utilization with the objective of identifying opportunities for heat integration. These models have also been used to study the implementation of new evaporation technologies and process integration measures (Wising, 2003; Bengtsson, 2004). However, the methodology used for the development of these models is not presented. In addition, the analysis focuses only on the energy aspects of the process without analyzing options for water reutilization and the interactions between the steam and water systems.

The development of a representative, reliable and focused model of an operating process is a prerequisite to the optimization and fine tuning of its energy performance. This model, referred to as base case process, should represent the actual process in its current configuration and operating conditions. It should be able to support a rigorous and detailed analysis leading to alternative, energy enhanced process designs that can be implemented in confidence. It should not contain unnecessary details which could hinder its utilization without improving the usefulness of the results produced. This critical and preliminary task is not always given the importance it deserves even though it is the foundation of all process analyses that may be later undertaken.

Guidelines and targets that identify process inefficiencies and areas of most likely gains should be formulated at the earliest stage of a retrofit project in order to channel efforts and ensure success of the development, assessment and selection of energy enhancement options. This task is referred to as benchmarking. A thorough and careful benchmarking analysis will later reduce the deployment of resources and commitment of expenditures.

A systematic stepwise method to construct a base case model that meets those criteria and to execute effectively the process benchmarking step has been developed and applied to a Kraft pulping mill in operation. The definition and characterization of the base case are presented in Part I of this paper, the benchmarking analysis in Part II. The anticipated sequence of this work, i.e., the identification of potential energy saving measures, their technical and economic evaluation and the formulation of an implementation strategy has now been completed and presented by (Mateos-Espejel et al., 2010b). The analysis has been based on a novel method which takes into account the interactions and synergies of all systems that impact upon the energy profile of the optimized process (Mateos-Espejel et al., 2010a,b).

Improving energy efficiency in chemical processes has become an important issue in times of volatile and increasing energy prices. In the case of the Canadian pulp and paper (P&P) industry, it is also part of a strategy to remain competitive in face of emerging pulp producing countries at a time when the demand for paper commodities, the traditional mainstay of the Canadian industry, is shrinking.

A wide variety of enhancing techniques is used to improve the energy efficiency of a feedstock transformation process. The extent of internal heat recovery and the degree of water reutilization are often the most important. A broad spectrum of methodologies has been developed to address the problem (El-Halwagi and Manousiouthakis, 1989; Linnhoff, 1993; Wang and Smith, 1994; Dhole, 1998). In a typical Kraft process, the larger the amount of water consumed and effluent produced, the more energy is required for heating, cooling, and pumping. Steam and water systems are usually analyzed independently, although they are strongly interconnected (Savulescu et al., 2005; Leewongtanawit and Kim, 2008; Mateos-Espejel et al., 2008). Thus, the focus of the base case model is the study of steam and water systems.

The model developed must provide detailed information on production, distribution, utilization and post-utilization treatment of those utilities. The reliability of the base case depends largely on the data used for its definition. Several sources of information must be consulted and the data must cover a range of operating conditions (e.g. winter and summer) so as to represent the main process variations. Simplifications introduced in the model must not modify the whole or sectorial configurations of the process which affect its energy efficiency. A computer simulation must be designed as a tool to evaluate improvement scenarios and as a source of data for analysis (Lundström et al., 2007). Its level of details will depend on its main purpose (Turon et al., 2005; Blanco et al., 2006; Dahlquist, 2008)

The case study presented below is based on an operating Kraft pulping mill located in Eastern Canada. The mill is part of an eco-industrial cluster and, in addition to making a high grade Kraft pulp, it exports steam to a nearby sawmill and treats the effluent of an adjacent town; district heating is under consideration.

2. Context

The Kraft process is the prevalent manufacturing technology by which wood chips are transformed into paper pulp, the intermediate material from which a very broad spectrum of finished or semi-finished paper products are made (Smook, 2002).

The core of the Kraft process is a chemical delignification step performed in a digester where the individual cellulosic fibers are separated to form the pulp. The delignification agent (white liquor) is a mixture of sodium hydroxide and sodium sulfide. After delignification the fibers are washed, and chemically bleached. Finally they are drained, pressed and thermally dried. A key characteristic of the process is that the spent delignification liquor, the black liquor, separated from the fibers in the washing step, is concentrated and burnt in the recovery boiler to produce steam. The spent inorganic chemicals form a smelt, composed of sodium carbonate and sodium sulfide, which is collected at the bottom of the recovery boiler. The smelt is dissolved to form the green liquor which is recaustified with quick lime produced on site in a lime kiln, to regenerate the white liquor. A simplified schematic of the complete Kraft process is given in Fig. 1.

The Kraft mill studied has an average production of 700 adt/d (adt = air dried tons) of high grade bleached pulp. The mill uses an 8 batch digester sequence for chemical delignification and a five stage bleaching sequence which uses different bleaching agents (ClO_2, H_2O_2, NaOH) at different conditions. The ClO_2 is manufactured on site. The concentration of the weak black liquor (BL) initially at 15% dissolved solids (DSC) or in suspension is performed in two steps; first, the BL is passed through a set of pre-evaporators driven by recycled steam to raise its DSC to 19% and then it is sent to two parallel trains driven by live steam to reach a final DSC of 75%. Drying is performed in two steps: first, the pulp passed through a set of cylinders where water is evaporated by indirect heating, and then hot air is used to attain the final specification of pulp consistency. A steam turbine is used to entrain the drying equipment.

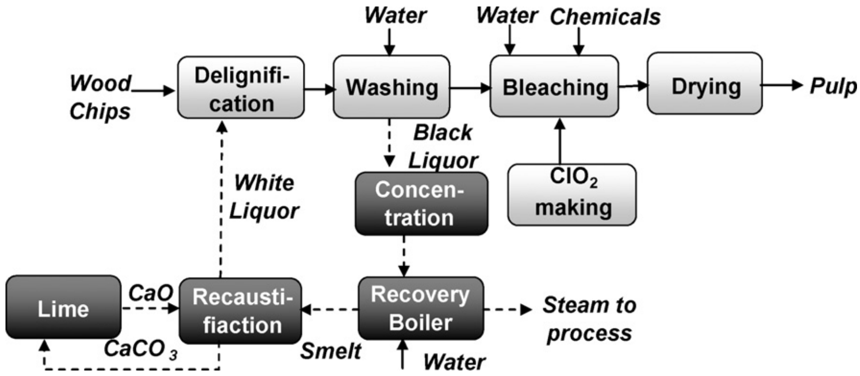

Fig. 1 – Simplified diagram of the Kraft process.

3. Methodology

The objective of this methodology is to detail the information required for the development of a base-case that will be used for a water and energy study. The aspects treated go beyond what is commonly encompassed in an water and steam audit. Audits usually focus on the identification of utility consumers and producers without specifying the type of process evaluation that will be perfomed. Audits are applied to water or steam but rarely include both systems in conjunction. The methodology presented deals with the water and steam together, and in addition it integrates other subjects critical to an energy efficiency study: data collection and treatment, definition of the process boundaries, characterization of steam and water networks and, the construction of a computer simulation. These issues must be reigorously treated in order to obtain a reliable simulation model that can be used for a complete and detailed evaluation of the process.

The base process simulation model is constructed in four steps:

- Data gathering
- Master diagram
- Systems analysis
- Simulation

The systematic application of these steps will help identify inefficiencies in the steam and water systems prior to the benchmarking analysis which will be the object of Part II.

3.1. *Data gathering*

The data to be collected should represent the thermal and water behaviour of the process over a long period of time (i.e., steam and water consumption for one year). This information can be obtained from the data acquisition system of the mill, from arechived data, and from the process and instrumentation diagrams (PIDs). PIDs are very useful as they contain details of the individual process units and process streams (i.e., temperatures, flowrates, concentration). The data collected should be particularly detailed for unit operations significantly affected by seasonal variations, changes in pulp production or recurrent technical problems. After gathering the data, a preliminary overall water and steam balance is performed to identify inconsistencies or a lack of information. The specifics about the production, utilization, and post-utilization of steam and water are discussed later in Section 3.3. The utilization of several sources of information helps to broaden the scope of the subsequent analysis as different operating conditions can thus be evaluated and possible operational problems pinpointed.

The difference between the data on steam production and consumption, and between water intake and water consumption must be assessed to detect possible gross errors.

3.2. *Master diagram*

A master diagram where the steam and water utility systems and all significant process streams are clearly identified is extracted from the PID's. The AUTOCAD software can be used to perform this task. The diagram contains the details of all process sections, and major unit operations, the recirculation loops, and connection between sections.

This diagram is an essential tool for the development of the computer simulation, as all process sections and their interconnections are identified. In addition, it will be used to construct the flow diagrams of the utilities systems, and to evaluate factors affecting the feasibility of energy efficiency measures such as the distance between the process streams and unit operations.

3.3. *Systems analysis*

Both systems are defined in detail. Data reconciliation should be peformed when large differences exist between production and utilization.

Some very important characteristics of the utilities are recorded at this stage:

- The various fuels used to produce steam
- Direct or indirect heating
- Percentage of condensate recovery
- Water temperature levels
- Water reutilization strategies
- Inefficiencies such as the utilization of make-up water without preheating or utilization of pressure release valves instead of cogeneration
- Sections with the highest consumption of water and steam.

This information is used as a guide to determine the level of details required in the simulation in the different part of the process.

3.4. *Computer simulation*

The process is simulated in a water-energy oriented perspective to study the interactions between the utility systems

Table 1 – Average mill data for the overall production and utilization of steam.

	Mass flow (t/h) measured data
Steam production description	
Biomass boiler (BI)	64.7
Fossil fuel boiler (FF)	29.5
Recovery boiler (RB1)	89.0
Recovery boiler (RB2)	37.5
Desuperheating water	55.7
Total	276.4
Steam utilization description	
Total MP	85.2
Total LP	170.2
Total HP	32.4
Total	287.8
Production – utilization	−11.4 (4% diff.)

and evaluate potential energy enhancement measures. The procedure developed for the construction of the simulation encompasses: the modeling of the process unit operations, the definition of the required level of details in the water and steam systems, the convergence of the simulation to a steady state and its validation.

The objective is to represent the unit operations as steam and water consumers. The starting points for the simulation flowsheet are the process master diagram and the utility systems flowsheets. The level of details used to describe specific process sections depends on their potential impact on the energy efficiency of the process. The simulation is validated by a comparison between simulated and measured data.

A real process is never in a true steady state; local adjustments of operating conditions, equipment turn over, feed rate variations, etc. cause constant fluctuations which affect steam and water consumptions. Moreover, measured parameter values contain noises or errors (random or gross) caused by imperfections of sensors and recording equipment. A simulation should hopefully represent a long term average state of the real process.

4. Case study

4.1. *Data gathering*

For this case study there are two principal sources of information: measured archived values for different years (2002–2003 and 2005 for steam; 2006 for water) and the PIDs. The data were extracted from this sample for the two periods with the highest consumptions; winter for steam and summer for water.

A low and very tolerable discrepancy of 4% (Table 1) was found for the steam data averaged over the 2005 winter period. This difference is within the range of process variability. The high cost of steam may have been a reason to maintain a good monitoring of all steam users. The same procedure was applied to the water system (Table 2) but a difference of 34% between water intake and consumption was observed. This large difference may be due to poor monitoring of water usage perhaps justified by its low cost. This is not a good practice however since very large quantities of water are used in a Kraft process at a temperature which is well above the intake temperature. The cost of water heating is a significant share of the mill energy bill. An analysis of the water streams in the PID's and a comparison to the current practices were used to

Table 2 – Average mill data for the overall input and utilization of water.

	Vol. flow (m^3/h) measured data
Input water description	
Treated water	2024.0
Screened water	1072.0
Total	3096.0
Water utilization description	
Treated	1186.3
Screened	861.8
Total	2048.2
Input – utilization	1047.8 (34% diff)

fill the gaps of the overall water balance and perform data reconciliation. These results are presented in Section 4.3.

4.2. *Master diagram*

All specific constituents of the flow networks have been traced: pulp, whitewater, black liquor, white liquor, green liquor, but also water and steam as well as condensates and effluents. Fig. 2 gives an overview of the master diagram indicating the number of available PIDs from which each section was developed. The process has been divided into three major parts: the steam system, the water system, and the pulping line. Water is used for dilution, washing, cooling, and steam production. Steam is used in chemical delignification, to heat up the fresh water, to concentrate the black liquor and for drying. The inputs to the process are the wood chips, the purchased fuel to satisfy the process steam needs, the municipal effluent from a nearby town treated by the mill and water. The outputs are dryed bleached pulp for shipment to paper product manufacturing mills, steam for sale to a sawmill, flue gases from the boilers, water returned to the environment and solid wastes.

The master diagram is a detailed description of how the utilities are produced, used in the process and their post-process utilization. In addition, it has been employed to identify possible process interactions compatible with the construction of a representative computer simulation diagram.

4.3. *Systems analysis*

The energy efficiency of a P&P process is strongly related to the proper management of steam and water. The data presented in this section deals with the efficiency of the boilers, and with the distribution of steam, condensates, water and effluents within each process section.

4.3.1. *Steam system*

Initially, total steam consumption and condensate production by each section was determined. Subsequently, all steam driven unit operations as well as condensate producers were located. For an energy study, the direct injections of steam should also be highlighted.

Production. Four boilers produce the necessary steam for the process: two use spent liquor as fuel (recovery boilers, RB1 and RB2), one uses wood residues (biomass, Bi) and the other fossil fuel (FF). They produce high pressure steam (HP = 3100 kPa), part of which is used for soot blowing, for pulp drying and to entrain the turbine that drives various equipment of the pulp drying machine; the rest is depressurized by pressure release

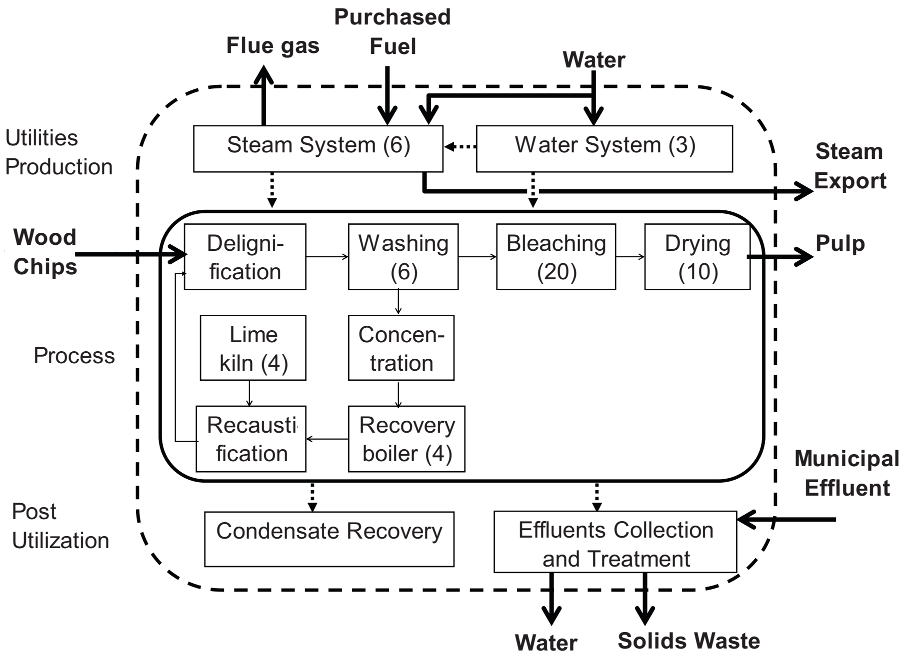

Fig. 2 – Overview of the master diagram.

valves (PRVs) and desuperheated to produce medium and low pressure steam (MP = 965 kPa; LP = 345 kPa). The efficiency of the boilers is computed by Eq. (1), results are given in Table 3.

$$\eta = \frac{\dot{m}^{v}(h_{out} - h_{in})}{\sum_{i} \dot{m}_{i}^{f} HHV_{i}} \quad (1)$$

η, efficiency of the boiler (%); $\dot{m}^{v}$, steam generated by the boiler (kg/s); h_{out}, enthalpy of the HP steam produced: 3160 kJ/kg (371 °C); h_{in}, enthalpy of the feed water to the boiler: 582.2 kJ/kg; $\dot{m}_{i}^{c}$, fuel feed rate used (kg/s); HHV_{i}, high heating value (kJ/kg). The efficiency of the recovery and biomass boilers is clearly below the Canadian average. The causes of their low efficiency can be a poor operation or deterioration of the equipment. The fossil fuel boiler is fired to meet the needs of the process beyond the steam production capacity of the recovery boilers; it should only be used to absorb fluctuations of pulp production rate or seasonal variations of the steam demand.

Utilization. Steam is used for different purposes throughout the process. Most of it is used as heat supply to process operations, the largest consumers being wood delignification, water deareation, black liquor concentration, and pulp drying including the turbine (Fig. 3). An appreciable proportion is used for heating water, pulp, and whitewater as well as for soot blowing in the boilers. MP steam is also sold to an adjacent sawmill. The steam pressure levels and the way in which it is used are important to the elaboration of energy efficiency measures. Steam can be either used for direct steam injection or indirect heat exchanges as shown in Table 4. The utilization of steam injection eliminates the possibility of condensate recovery.

Post-utilization. The condensate recovery rate of the process is 46.3% (109.9 t/h) as shown in Fig. 4. This is below the Canadian average of 75% and even below the average for old mills (the mill of the case study is in this category), which is 60% (Bruce and Wilson, 1999). Replacing steam injection by indirect heat exchange could significantly increase the rate of recovery. The contaminated condensates, which contain traces of compounds which could affect the efficiency of the boilers, cannot be returned to the steam network but their energy content which is appreciable could be used to preheat fresh water or other process stream below 100 °C. The recovered condensates and cold make up water are mixed up and heated by steam injection in the deareator (Fig. 5). This unit accounts for 12.6% of the total steam consumption. The amount of steam required depends on the amount of condensate recovered and

Table 3 – Boiler efficiency and steam production.

Boiler	Average (MW)	Max. (MW)	Eff. η (%)	Can. aver. η^{a} (%)
RB1	63	65	53	65
RB2	41	41	53	65
Bi	42	47	43	64
FF	15	25	87	64
Total	161	178		

Max = maximum; Can. aver. = Canadian average; Eff. = efficiency.
[a] Francis et al. (2006).

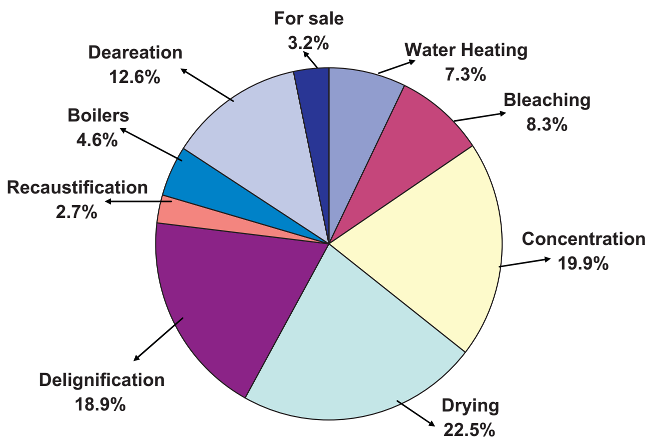

Fig. 3 – Energy consumed by process department as a fraction of the total consumption.

Table 4 – Direct or indirect steam utilization by process section.

	HP		MP		LP	
	Dir	Ind	Dir	Ind	Dir	Ind
Delignification			√	√		
Bleaching					√	
Drying		√			√	√
Concentration				√	√	√
Recaustification						√
Deareation					√	
Water heating						√
Boilers	√					

Dir = direct heating; Ind = indirect heating.

the temperature of the cold make up water. It is important to identify the sections where condensates are not recovered. Fig. 6 depicts the distribution of steam to the process sections and the points of condensate recovery. The pulp washing equipment and the lime kiln do not consume steam. In conclusion, the key issues to be considered in an energy efficiency enhancement program for this mill should be:

- Internal heat recovery
- Condensate recovery
- Boilers efficiency
- Steam injections
- Pressure steam levels

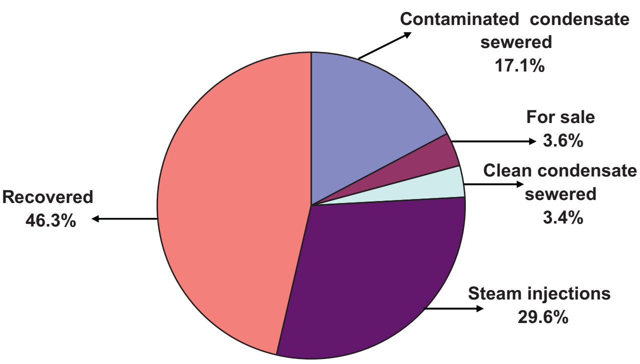

Fig. 4 – Distribution of condensates in the process.

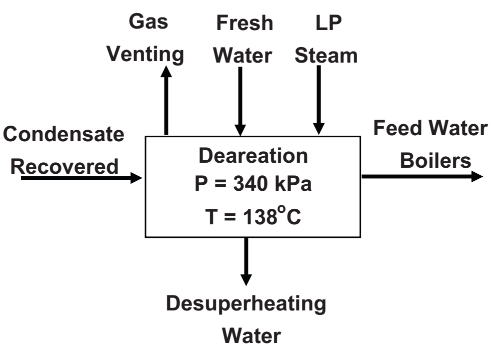

Fig. 5 – Deareation system.

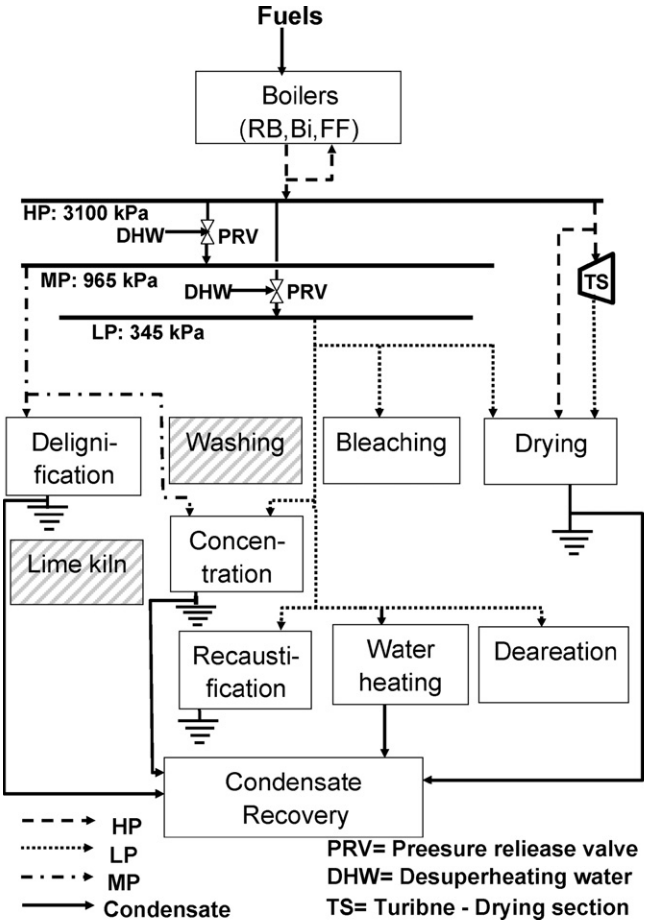

Fig. 6 – Simplified diagram of the production, utilization and post-utilization of steam.

4.3.2. *Water system*

Water is used for a broad variety of purposes: pulp washing and diluting, cooling, heating of a great variety of process streams and for steam production. As mentioned earlier, there is a large fraction of the water usage which is not accounted for by the mill. Data reconciliation using the process simulation and the ASPEN Water software was applied to generate a representative set of data for the water system. Data reconciliation has been previously used in the P&P industry prior to a systems closure analysis (Jacob and Paris, 2003b; Brown et al., 2004)

Data reconciliation is performed to generate a set of data that satisfies all process equations and constraints from a set of measured data that do not. It requires excess data values (redundancy) distributed over the system considered. This can be solved by the least squares method if the formulation is based on linear equations (Jacob and Paris, 2003a). The software requires the input of the water system diagram, the mass flowrate for each water stream, and the level of accuracy of the data (very low, low, medium, very high). Most of the individual users, including the ones that are not monitored by the mill were identified from the PIDs. The level of accuracy is typically estimated from the redundancy of the data. However, due to the lack of measured values, the accuracy was determined for each process section from differences between the PID and measured values and a comparison to the current practices for an old mill (Carter and Gleadow, 1994). The larger the difference between the information sources the lower the accuracy. The reconciled data encompass 94.2% of the feed water to the process. The other 5.8% will be considered as unaccounted in the water balance. Savulescu and Alva-Argaez (2008) reported a percentage of 90% for their water study. The water information given in this and the following sections is based on the reconciled data.

Production. About 60% (1750 m^3/h) of the feed water is screened and chemically demineralized for steam production

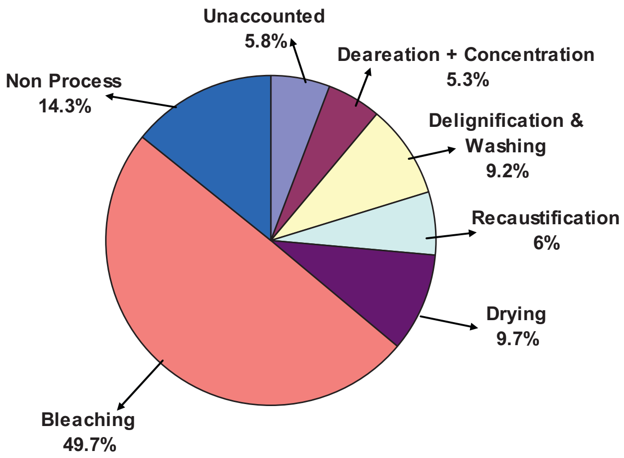

Fig. 7 – Water consumption distribution in the process.

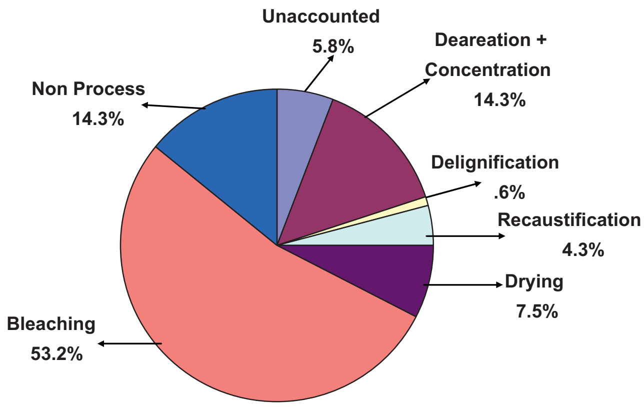

Fig. 8 – Distribution of sewered effluents in the process.

and for use in operations where it is mixed with the pulp, for example in pulp washing, bleaching and drying; it will be referred to as treated water. The remaining 40% (1160 m^3/h) is only screened and it is used for indirect cooling, steam scrubbing and housekeeping: it will be referred to as screened water. The treated water is used at 3 temperature levels: cold (winter: 4 °C, summer: 20 °C), warm (44 °C), and hot (58, 62 and 71 °C). The warm water is obtained by cold water heating in the condensers of the black liquor concentration unit. Hot water at 58 °C is produced by indirect heat exchange with the effluents from the concentration section. To produce the rest of the hot water the following procedure is followed: the temperature of the warm water is increased to 53 °C by means of internal heat recovery, then to 62 °C using direct steam injection in the hot water tank. Part of the water at 62 °C is used by the process and the rest is heated to 71 °C by indirect heat exchange with steam.

Utilization. Screened cold water is used for housekeeping, cooling in the ClO_2 making section, and gas washing. Treated cold water is used as make up in the deareator, for the production of ClO_2, and to seal vacuum pumps. Warm water is used in the pulp washers and for dilution in the recaustification. Hot water is used for washing in the bleaching stages and for dilution in the pulp drying and chemical production sections. Fig. 7 presents the distribution of water consumption in the process. With almost 50% of the total consumption, bleaching is the largest consumer. Water usage impacts the energy consumption and this effect must be taken into account in the formulation of energy enhancement measures. For instance, bleaching represents 15.6% of the total energy consumption because steam is used for pulp bleaching and to produce the hot water required in this section (Fig. 3). Water reduction in bleaching will, therefore, directly reduce the consumption of steam and the production of effluents. The non-process sections encompass the consumption of cold water for house keeping, filters cleaning, air conditioning, pump sealing, and floor hosing.

Post-process utilization. The post-process utilization of effluents consists of their direct recycling within the process and the usage of their heat content for internal heat recovery. The objective is to reduce water and steam consumption. Part of the bleaching effluents (49%) and drying filtrates (60%) are recycled to the pulp washing and bleaching sections respectively. The effluents from concentration at about 70 °C are used to heat up the cold water before it is sewered. All screened water used and the effluents produced by the vacuum pump seals, and by the recaustification, delignification, and boiler sections are directly sewered. Fig. 8 gives the origin of the sewered effluents. The temperature of the effluents coming from the bleaching and drying sections is about 70 °C, however their energy content is wasted. Ways to reuse these effluents in the process or to recovery their heat content by heat exchange must be considered.

Fig. 9 is a simplified diagram of the water system. A section for non-process uses has been included; it represents most of the cold water consumption (screened and treated). The delignification and concentration sections and the boilers are non-water users, but they receive steam by direct injections and produce effluents. The unaccounted water and, the water input with the wood chips and the water output with the pulp is also taken into account. The effluents from the boilers include the water evaporated in the flue gases and in the deareator. The effluents from pulp drying section effluents include the water evaporated from the pulp. The overall consumption of steam and water is presented in Tables 5 and 6. The measured data values will be compared with the results of the simulation in the next section. Several factors affect the performance of water and energy systems. Some of them concern to the overall process, such as fossil fuel utilization and cogeneration, and others are linked to specific practices, for example direct heating, non-isothermal mixing, and effluent reutilization.

Fossil fuel utilization: The need for fossil fuel is caused by the low efficiency of the boilers and insufficient internal heat recovery. The Kraft process generates most of its energy requirements by BL combustion and, in theory, it could be energetically self-sufficient (McIlroy and Wilczinsky, 1999). The utilization of fossil fuel in the case study is a sign of poor energy performance.

Cogeneration: The utilization of throttling valves to depressurize the HP steam wastes the potential of producing power, which can be an additional revenue to the mill.

Direct heat transfer and non-isothermal mixing: The direct injection of steam and the mixing of streams at different temperature levels are common practices to achieve target temperatures. However, these measures cause an energy degradation, which is generally ignored (Savulescu and Alva-Argaez, 2008). In the case study this occurs in the mixing of cold and hot water to produce the necessary warm water and in the direct steam injection into the hot water tank and the deareator. The impacts of these practices on the energy efficiency of the mill should be evaluated

Reutilization of condensates from the concentration section: These condensates generally have a low contamination level

Table 5 – Steam consumption and condensate recovered by process section.

Process section	Steam consumption		Condensate recovered
	GJ/adt	t/h	t/h
Delignification	3.99	54.3	20.3
Bleaching	1.75	23.8	15.6
Concentration	4.2	55.5	30.2
Drying	4.76	63.1	34.5
Water heating	1.54	20.3	9.3
Recaustification	0.57	4.9	–
Deareation	2.66	35.8	–
To sell	0.69	8.4	–
Boilers, and other equipments	0.98	6.4	–
Total process consumption	21.14	272.5	109.9

(Sankari et al., 2004), and they can be reused in other sections of the process. Since their temperature is above 70 °C, they could be reused to replace hot water, thus saving water and steam.

The detailed definition of the utility systems and the master diagram are the structures from which the simulation has been constructed. The analysis performed gives an overview of the current energy efficiency of the process. At this stage, only some process inefficiencies are identified, but this is the starting point for the benchmarking analysis.

4.4. *Computer simulation*

The method presented to construct a computer simulation includes all characteristics of the steam and water systems pinpointed in the previous sections. All steps taken for the development of the simulation are aimed at facilitating the water-energy analysis.

CADSIM Plus has been used to simulate the process. It contains models of all standard P&P unit operations, typical components (fibers, dissolved solids, water, steam, bleaching chemicals) and representative operating conditions as default values (temperature for delignification, pressure and pressure drop in the concentration section, consistency at the input and output of each section).

4.4.1. *Simplifications and required level of details*

The utility systems have been simulated in detail (Figs. 6 and 9). Sections, such as bleaching, drying, black liquor concentration, and recovery boilers that directly affect steam and water consumption, were also modeled in detail. Simplified models were used for the recaustification section and lime kiln which are not large consumers of steam (Table 5). Missing information and non-matching boundary data were estimated by partial heat and mass balances. Several simplifications were introduced:

- Combining or regrouping duplicate equipment such as tanks, washers, screeners, sieves, knotters, and mixers.
- The eight batch digesters were represented as only a single continuous digester.

The following components were specified for each stream as appropriate: water, fibers and total dissolved solids (organic and inorganic materials). A detailed composition of the dissolved solids was not necessary as its impact on the energy balance is negligible.

Table 6 – Water consumption by process section.

Process section	Water inputs		Effluents	
	m^3/adt	m^3/h	m^3/adt	m^3/h
Water intake				
Treated water				
Delignification & Washing	10.1	295.7	0.7	19.4
Bleaching	30.7	896.6	34.6	1008.3
Concentration	1.0	28.2	15.8	459.9
Drying	10.7	312	8.3	241.7
Recaustification	2.0	58.6	–	–
Deareation	4.8	138.7	–	–
To sell	–	–	–	–
Boilers	0.2	4.4	–	–
Non-process uses	4.6	134.0	4.6	134.0
Screened water				
Bleaching	24	700.6	24	700.6
Recaustification	4.6	132.8	4.6	132.8
Non-process uses	11.1	323.8	11.1	323.8
Delignification – water in chips	1.6	46.3		
Water evaporated – (flue gases, drying, deareator)	–	–	1.8	52.6
Drying–water out with pulp	–	–	0.07	2
Unaccounted	6.4	186.9	6.4	186.9
Total process consumption	110.1	3212.2	110.1	3212.2

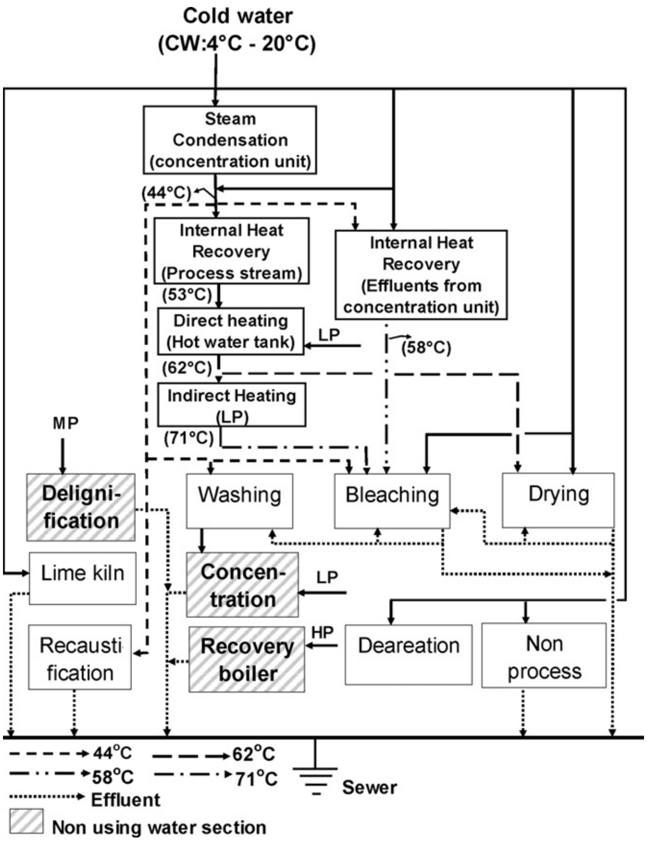

Fig. 9 – Simplified diagram of the production, utilization and post-utilization of water.

Direct injections of steam and mixing of streams of different temperature in tanks or process lines have been highlighted.

4.4.2. *Data specification*

The flowrates of steam were computed by specifying the target temperature of a determined process stream. Specifying the outputs from unit operations was avoided and instead, split ratios, concentrations, or mathematical relations between process streams were introduced. This procedure facilitates the adjustment of the simulation if the production rate, ambient temperature or other operating parameters are modified.

Table 7 – Overall production and utilization of steam.

	Mass flow (t/h)		
	Simulated data	Measured data	% diff.
Steam production			
Biomass boiler (BI)	64.8	64.7	0.1
Fossil fuel boiler (FF)	27.5	29.5	6.9
Recovery boiler (RB1)	88.8	89.0	0.2
Recovery boiler (RB2)	55.8	55.7	0.1
Total HP steam production	236.8	238.9	0.9
Desuperheating water	35.8	37.5	4.7
Steam utilization			
Total MP utilization	84.8	84.0	1.0
Total LP utilization	155.1	168.3	7.9
Total HP utilization	32.6	32.4	0.6
Total steam utilization	272.5	284.7	4.3

An Excel spreadsheet was used to transfer parameter values to the simulation (T, P, flowrates) and to extract data for subsequent analyses. This procedure helps identify and compute variations in the consumption of steam and water produced by the implementation of energy enhancement measures or modifications to the operating conditions.

All unit operation models were taken from the CADSIM libraries. Specific information was required to simulate the equipments.

- Washers: displacement and dilution factors
- Digesters and bleaching reactors: reactions yield and heat of reaction
- Recaustification and lime kiln: reaction yield, heat of reaction and stoichiometry
- Black liquor concentration: target dissolved solids concentration, and pressure
- Pulp drying: target pulp consistency
- Heat exchangers and deareator: target temperature
- Boilers: target temperature and pressure
- Pressure release valves: target pressure

4.4.3. *Simulation strategy*

The simulation diagram contains 22 main internal recirculation loops: water reutilization in pulp washing, bleaching and drying sections, reutilization of white liquor and green liquor

Table 8 – Water intake and utilization.

	Volumetric flow (m^3/h)				
	Simulated data	Measured data	% Diff.	PID	% Diff.
Water intake					
Treated water	1749.7	2024.0	13.6	–	–
Screened water	1159.4	1072.0	8.2	–	–
Total water intake	2909.1	3096.0	6.0		
Water utilization					
Cold water	633.7	476.9	24.7	690.5	151.6
Warm water	332.8	142.0	134.4	224.4	32.6
Hot water	783.2	567.4	38.0	1022.7	23.4
Cold screened water	1159.4	861.8	34.5	326.9	71.8
Total water utilization	2909.1	2048.2	29.6	2264.5	22.2
Water in with wood chips	46.3				
Direct steam injections	69.9				
Unaccounted	186.9				
Total water consumption	3212.2				

and, condensate recovery. More than 130 individual pieces of equipment have been simulated: digester, tanks, washers, dryers, evaporators, flash tanks, mixers, boilers, deareator, and separators. Since this level of detail increases the number of iterations for convergence, a simulation sequence was established: first, all sections were simulated individually until convergence was achieved; then the sections were connected to accomplish a global convergence.

4.4.4. *Simulation validation*

The difference between measured and computed values for the production of steam is 0.9% (Table 7). All individual steam-using operations have differences below 10%. Table 8 shows a difference of 6% between the computed water intake and the measured value.

5. Conclusions

The methodology presented fills an existing void of a structured approach for the development of the base case in energy efficiency studies. The systematic methodology defines and characterizes the base case in a water and energy oriented perspective.

The methodology integrates the stages required for the development and analysis of the water and steam systems that are the foundation of further more detailed analyzes. As a result of its application, a water-energy simulation model is constructed and insights about the overall energy efficiency are obtained.

The nominal conditions of the process have been established. The sources of information were measured data, and PID's. The construction of a master diagram based on all PID's is a novel approach to identify all water and steam users. Data reconciliation was used as a tool to overcome the lack of measured data in the water system. It was also possible to identify procedures and operations that affect the energy efficiency such as: non-isothermal mixing points, the low efficiency of the boilers, utilization of fossil fuel, lack of cogeneration and water reutilization. All unit operations were simulated as steam and water consumers. A key characteristic is that the level of detail for simulating the process sections varies in accordance with their water and steam consumption.

This procedure establishes the framework for water and energy analysis. Part II presents the benchmarking of the case study, in which the efficiency of the process systems is determined and the potential for internal heat recovery and water reutilization is estimated. Energy and exergy indicators have been defined to take into account the quantity and quality of the energy available and wasted in the process.

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References

Axelsson, E., Berntsson, T., 2005. Pinch analysis of a model mill: economic and environmental gains from thermal process-integration in a state-of-the-art magazine paper mill. Nordic Pulp and Paper Research Journal 20 (3), 308–315.

Axelsson, E., Olsson, M.R., Berntsson, T., 2006. Heat integration opportunities in average Scandinavian kraft pulp mills: pinch analyses of model mills. Nordic Pulp and Paper Research Journal 21 (4), 466–475.

Bengtsson, C., 2004. Novel process integration opportunities in existing kraft pulp mills with low water consumption. Ph.D Thesis. Department of Chemical Engineering and Environmental Science. Götenborg, Sweeden, Chalmers University of Technology.

Blanco, A., Dahlquist, E., Kappen, J., Manninen, J., Negro, C., Ritala, R., 2006. Modelling and simulation in pulp and paper industry. Current state and future perspectives. Cellulose Chemistry and Technology 40 (3–4), 249–258.

Brown, D., Marechal, F., Heyen, G., Paris, J., 2004. Data reconciliation and sampling protocol design. Case of a paper deinking process. Paperi ja Puu 86 (7), 565–570.

Browne, T.C., 1999. Réduction des coûts énergétiques dans l'indurstrie des pâtes et papiers. PAPRICAN, Montreal, Canada.

Bruce, D., Wilson, R., 1999. Chapitre 9: Centrale thermique, production d'énergie et traitement des effluents. Réduction des coûts énergétiques dans l'industrie des pâtes et papiers. Paprican, Montréal, pp. 189–205.

Carter, D.N., Gleadow, P.L., 1994. Chapter 4: Water Use Reduction in Chemical Pulp Mills. Water Use Reduction in the Pulp and Paper Industry. P. Turner. PAPRICAN, Vancouver.

Dahlquist, E. (Ed.), 2008. Use of Modeling and Simulation in Pulp and Paper Industry. COST office.

Dhole, V.R., 1998. Fluid Efficiency. U. P. 5824888. US, Linnhoff March limited. 5824888.

El-Halwagi, M.M., Manousiouthakis, V., 1989. Synthesis of mass exchange networks. AIChE Journal 35 (8), 1233–1244.

Francis, B., Towers, M., Browne, T., 2006. Benchmarking energy use in pulp and paper operations. In: Proceedings of the 92nd PAPTAC Annual Meeting, Montre al, QC, pp. A55–A61.

Jacob, J., Paris, J., 2003a. Data sampling and reconciliation – application to pulp and paper mills. Part I: methodology and implementation. Appita Journal 56 (1), 25–29.

Jacob, J., Paris, J., 2003b. Data sampling and reconciliation, application to pulp and paper mills. Part II: case studies. Appita Journal 56 (2), 116–121.

Klugman, S., Karlsson, M., Moshfegh, B., 2007. A Scandinavian chemical wood-pulp mill. Part 1: energy audit aiming at efficiency measures. Applied Energy 84, 326–339.

Leewongtanawit, B., Kim, J., 2008. Synthesis and optimisation of heat-integrated multiple-contaminant water systems. Chemical Engineering and Processing 47, 670–694.

Linnhoff, B., 1993. Pinch analysis – a state-of-the-art overview. Chemical Engineering Research and Design 71, 503–522.

Lundström, A., Von Schenck, A., Samuelsson, A., 2007. Process Simulation – A Tool for Process Improvements. PulPaper 2007 Conference: Innovative and Sustainable Use of Forest Resources. Finish Paper Engineer's Association, Helsinki, Finland.

Mateos-Espejel, E., Marinova, M., Bararpour, S., Paris, J., 2008. Energy implications of water reduction strategies in Kraft process. Part II: results. In: PAPTAC 94th Ann. Mtg, Montreal, Qc. A, pp. 219–223.

Mateos-Espejel, E., Savulescu, L., Marechal, F., Paris, J., 2010a. Systems interactions analysis for the energy efficiency improvement of a Kraft process. Energy (in press).

Mateos-Espejel, E., Savulescu, L., Marechal, F., Paris, J., 2010b. Unified methodology for thermal energy efficiency improvement: Application to Kraft process. Chemical Engineering Science (in press).

McIlroy, D., Wilczinsky, J., 1999. Usines de pâte chimique. Réduction des coûts énergétiques dans l'industrie des pâtes et papiers. T. Browne. Paprican, Montreal, pp. 89–112.

Sankari, M., Sillanpaa, M., Ala-Kaila, K., Dahl, O., 2004. Use of secondary condensates from black liquor evaporation as process water in D_o bleaching. Pulp and Paper Canada 105 (5), 36–40.

Savulescu, L., Kim, J.-K., Smith, R., 2005. Studies on simultaneous energy and water minimisation – Part I: systems with no water re-use. Chemical Engineering Science 60 (12), 3279–3290.

Savulescu, L.E., Alva-Argaez, A., 2008. Direct heat transfer considerations for improving energy efficiency in pulp and paper Kraft mills. Energy 33, 1562–1571.

Smook, G.A., 2002. Handbook for Pulp & Paper Technologists. Angus Wild Publication Inc., Vancouver, Canada.

Turner, P., 1994. Water Use Reduction in the Pulp and Paper Industry. Canadian Pulp and Paper Association, Vancouver, Canada.

Turon, X., Labidi, J., Paris, J., 2005. Simulation and optimisation of a high grade coated paper mill. Journal of Cleaner Production 13 (15), 1471–1480.

Wang, Y.P., Smith, R., 1994. Wastewater minimisation. Chemical Engineering Science 49 (7), 981–1006.

Wising, U. 2003. Process integration in model Kraft pulp mills. Ph.D Thesis. Department of Chemical Engineering and Environmental Science. Göteborg, Chalmers University of Technology.