Chemical Engineering Science 66 (2011) 135–151

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Unified methodology for thermal energy efficiency improvement: Application to Kraft process

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ARTICLE INFO

Article history:
Received 11 November 2009
Received in revised form
21 September 2010
Accepted 24 September 2010
Available online 1 October 2010

Keywords:
Energy
Water
Exergy
Pinch analysis
Integration
Kraft process

ABSTRACT

A unified methodology that can be used to identify the interactions between the utilities systems and the process, as well as their impacts on the implementation of energy efficiency measures is presented. It takes into account steam and water systems to analyze the process and formulate energy enhancement measures. It has been applied to an operating Kraft mill in Eastern Canada. The methodology consists of five stages: base-case process definition and characterization, pre-benchmarking, systems interactions analysis, implementation strategy and post-benchmarking. A simulation focused on the energy and water systems is first developed and used as basis of the analysis. The pre-benchmarking characterizes the current energy efficiency of the process by three techniques: energy and exergy content indicators, comparison to the current industrial practice and establishing targets for minimum energy and water requirements determined by the Thermal Pinch and Water Pinch methods. The systems interactions are analyzed to develop complementary energy efficiency measures by applying several energy enhancing techniques. A three-phase strategy is proposed to implement the identified measures. The application of the unified methodology results in an eco-friendly process that does not require fossil fuel for steam production and generates revenues by producing green electricity from biomass. In the case study presented, very significant energy gains have been proposed (26.6% steam requirement reduction and 33.6% fresh water intake reduction).

1. Introduction

The enhancement of the energy efficiency of processes is of paramount importance for the energy intensive chemical industries that still rely on expensive fossil fuels. The globalization of markets has led the industries to reduce all costs, including that of energy, without reducing the quality of the end product. The implementation of energy reduction programs is essential to enable manufacturing industries in industrially mature countries to remain competitive. Increased awareness of the importance of energy efficiency in the context of environmental sustainability has led governments to implement programs and incentives in support of energy enhancement in the manufacturing sector and other areas. The industry has responded by developing methodologies and technologies aimed at improving the chemical processes. These methodologies tend to focus on specific enhancing techniques and on specific process sections without regard to the interactions between the utility systems, water and steam, and unit operations. The application of individual techniques will indeed lead to the decrease of energy consumption of a plant but they will not accomplish the full reduction potential.

A preliminary step to the process analysis, often overlooked, is the definition of the base-case. It consists of developing the process and utility systems diagrams and, the overall steam and water balances. The construction of a computer simulation, representative of the complete process, is fundamental for any energy study (Paris, 2000). The simulation is the principal source of data and also an instrument to assess the impacts of possible process modifications. The evaluation of the process sections or units is achieved by benchmarking (Towers and Turner, 1998; Francis et al., 2006). Benchmarking typically consists of comparing a given process with the industrial practices. However, the results of this analysis do not provide information on the means to improve the process. Paris (2000) proposed a systematic approach for implementing water reutilization measures that can also be extended to the improvement of the energy efficiency. This approach consists of three sequential steps: good housekeeping, good engineering practice and advanced energy optimization. Measures to improve pipes isolation, stop leaks and take other simple measures should be implemented first. The optimization of the operating conditions and the control systems should be performed before applying more complex energy enhancing techniques.

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doi:10.1016/j.ces.2010.09.032

The energy enhancing techniques most frequently utilized are internal heat recovery, water reutilization and energy conversion and upgrading. To this end, milestone methodologies such as Pinch analysis®, Water Pinch and Exergy Analysis have been developed. The objective of Pinch analysis® (Linnhoff et al., 1982) is to increase process to process heat exchanges by the design of an optimum retrofit heat exchanger network (HEN). It was first applied with success to complex industrial sites such as petroleum refineries. It can incorporate complementary techniques such as energy conversion and upgrading. Water Pinch (El-Halwagi and Manousiouthakis, 1989; Wang and Smith, 1994; Dhole, 1998) is an extension of Pinch Analysis® but in a water reutilization perspective. Its objective is to maximize the reutilization of water streams within the process or to determine appropriate water regeneration measures.

Exergy is a measure of both the quality and quantity of the energy involved in transformations within a system and the transfers across its boundary. The internal destruction of exergy is associated with the irreversible transformations that occur in the system; examples relevant to this work are the destruction of exergy caused by heat transfer in the heat exchangers and by the adiabatic expansion of a steam in a valve. Therefore, the exergy is an indicator of the inefficiencies of a process. Exergy analysis is an approach based on the principle of exergy destruction and exergetic efficiency used to analyze the performance of certain operations or identify the bottlenecks of a process (Kotas, 1985; Szargut and Morris, 1988). The objective is to propose enhancement measures that reduce the exergy destroyed by the way the process operations are performed. Exergetic efficiency is a term that can have several interpretations (Brodyansky et al., 1994) and that may lead to different results. Moreover, the concept of exergy might seem unrelated to the engineering practice when compared to other more familiar quantities such as enthalpy and concentration. In fact thermal pinch, water pinch and exergy analysis complement each other and should all be part of a unified methodology for the improvement of the energy efficiency. They have been combined to analyze specific sections of a process. Staine and Favrat (1996) proposed the utilization of exergy composite curves for the energy optimization of a process in the context of a life cycle analysis. In this representation, the exergy destroyed in a heat exchange is graphically displayed as a function of the temperature approach; it can thus be used to determine a realistic efficiency compatible with heat exchange conditions. This method is also used to quantify the exergy destroyed in the production and utilization of steam as shown by Brown et al. (2005) and Mateos-Espejel et al. (2007). Sorin and Paris (1999) integrated exergy and pinch analysis for improving the operating conditions of a process and the retrofit of the HEN. They introduced the concept of transit exergy (Sorin et al., 1998) in the computation of the exergetic efficiency. Marechal and Favrat (2005) demonstrated the combined used of exergy analysis and process integration techniques to analyze the implementation of utility systems in industrial processes. Linnhoff and Alanis (1991) applied Pinch Analysis® and Gaggioli et al. (1991) exergy analysis separately to the same case study. Their results only highlight the domains of action for each methodology. Exergy analysis identifies the operations with poor performances and Pinch Analysis® the heat transfer inefficiencies or lack of internal heat recovery.

The interactions between water and energy have also been studied. Savulescu et al. (2005) proposed a method to reduce water and steam consumption in water networks by the utilization of a two-dimensional grid diagram. This diagram incorporates the temperature and contaminants concentration in order to develop complementary measures for internal heat recovery and water reutilization. Leewongtanawit and Kim (2008) extended the method proposed by Savulescu et al. (2005) to consider mathematical optimization and multiple contaminants. Schaareman et al. (2000) applied Pinch Analysis® and Water Pinch in sequence but without analyzing the impacts of water reutilization strategies on the thermal side of the process. Savulescu and Alva-Argaez (2008) proposed a methodology for the appropriate utilization of non-isothermal mixing used for direct heat recovery, to reduce the steam demand in water and steam systems. In regard to exergy and water studies, Asselman et al. (1996) employed the exergetic efficiency, to choose the appropriate equipment for water regeneration.

Energy upgrading is performed by external devices such as absorption heat pumps. Absorption heat pumps is an energy technology that can upgrade low temperature heat by exploiting the effect of pressure on an absorption–desorption cycle (Ziegler and Riesch, 1993). They can reduce the heating and cooling requirements if their positioning into the process respects the pinch rules (Bakhtiari et al., 2007). Absorption heat pumps have been used in combination with pinch analysis (Marinova et al., 2007; Bakhtiari et al., 2009) to increase the energy savings achieved by an energy reduction program.

A unified methodology for improving the energy efficiency of a process in a global process perspective has been developed and is presented below. The definition and characterization, and the benchmarking analysis of the process base-case are done in a steam and water perspective. Several energy enhancing techniques are combined and their effects on the process systems identified and taken into account. Energy, water and exergy indicators are used to asses cumulative enhancements. An implementation strategy considering technical and economic constraints is finally proposed. The methodology is illustrated by a case study based on an operating Kraft pulping process situated in Eastern Canada, which is characterized by strong interactions between the steam and water systems.

2. Context

The pulp and paper industry is Canada's most energy intensive sector, accounting for 25% of the total industrial energy consumption (CIPEC, 2007). Even though 60% of its energy requirement is generated from biomass, the industry still uses large amounts of fossil fuel. In addition to its oil dependency, high water consumption adds to its energy challenge (Turner, 1994). Overall, energy accounts for up to 30% of the total pulp manufacturing cost in Canada.

The Kraft process is the prevalent manufacturing process 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). A simplified schematic of the complete Kraft process is given in Fig. 1. 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; ClO_2 is a bleaching agent produced on site. Finally the fibers are drained, pressed and thermally dried. A key characteristic of the process is that the spent delignification liquor (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 green liquor which is recaustified with quick lime produced on site in a lime kiln to regenerate the white liquor.

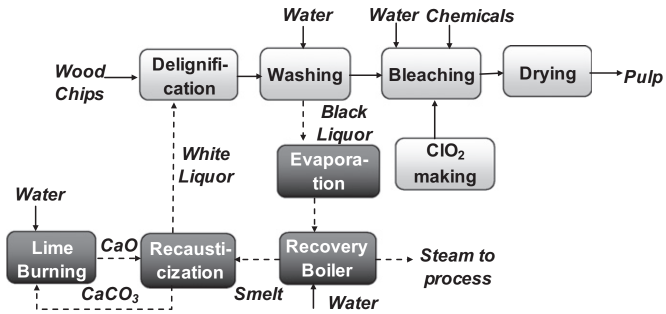

Fig. 1. Simplified diagram of the Kraft process.

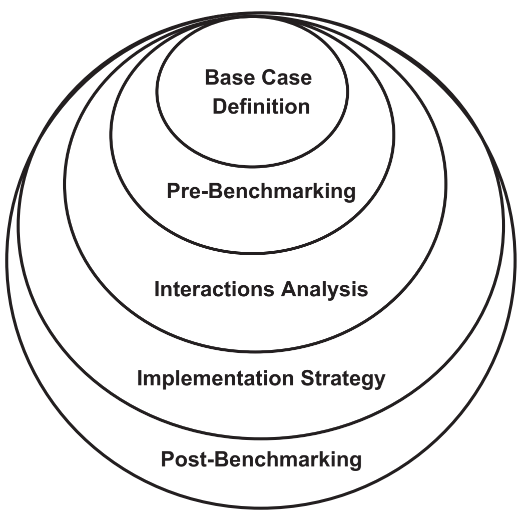

Fig. 2. Unified methodology.

The energy efficiency of the Kraft process is strongly related to the proper management of water and steam that are the driving forces of the process. Water is used for cooling, dilution, pulp washing, and for steam production. Steam is employed for the chemical delignification, to heat up fresh water, to concentrate the black liquor and for pulp drying.

3. Unified methodology

The onion diagram commonly used in process design has been modified to represent the unified methodology. This methodology has two principal objectives:

- the appropriate definition and analysis of the base-case and
- the development of energy enhancement measures that take into account the interactions of the utility and process systems and, the economic and technical constraints.

The methodology consists of five stages as shown in Fig. 2. The inner ring represents the base-case definition. A computer simulation focused on the energy systems is developed in this step. The second ring corresponds to the pre-benchmarking analysis. The base-case is evaluated by comparison of its efficiency to the current practice of the industry and by the application of energy and exergy content indicators. The minimum energy and water requirements of the process are also determined in this stage. The third ring is the core of the methodology; it represents the formulation of technically feasible energy enhancing options. Several techniques are available to improve the energy performance of a process: internal heat recovery (IHR), water reutilization (WR), condensates return (CR), energy upgrading (EU), energy conversion (EC), and elimination of non-isothermal mixing (NIM). They are applied to specific energy systems on the utility or process side (steam production and distribution, hot or cold water networks, process heat sources and sinks, etc.). Since those systems are interconnected, actions taken on one of them may have effects on another. These effects can be positive (synergies) or negative (counter-actions). A systematic, stepwise procedure has been developed to ensure that synergies are exploited and counter-actions avoided. The most advantageous results are identified and retained. The fourth ring is the implementation strategy. A three-phase strategy was selected for the specific base-case in the context of its management strategic plan: the elimination of fossil fuel, the liberation of steam and the production of power. The fifth ring is the post-benchmarking which is performed to quantify the improvement of the energy efficiency. A detailed diagram of the unified methodology, indicating the steps contained in each stage, is shown in Fig. 3.

3.1. Stage 1: base-case

The development of a focused, reliable and representative model of an operating process is a prerequisite to the improvement of its energy performance. This model that will be referred to as base-case represents the current steady state of all process units. A four-pronged procedure (Fig. 3) is used to define the base-case nominal conditions: data gathering, elaboration of a master diagram, systems analysis, and simulation. The details for each step can be found in Mateos-Espejel (2009); they are summarized below.

Data gathering: The data to be collected should represent the thermal and water performance of the process over a long period of time (e.g., steam and water consumption for one year). The sources for this information are the data acquisition systems, archived values or Process and Instrumentation Diagrams (PID). If necessary on-line measurements should be performed. The differences between data on steam production and on steam consumption, and between water intake and water consumption must be carefully examined to detect possible gross errors.

Master diagram: A master diagram is constructed with data extracted from the PIDs. The water and steam utility systems and all significant process streams should be identified. This diagram can be used to identify process simplifications so as to construct a manageable yet representative computer simulation.

Systems analysis: Detailed flow diagrams of the steam and water networks are extracted from the master diagram. They contain all key stream parameters (flowrates, temperatures and pressures). They also indicate the heat production nodes (fuels, boiler efficiencies, steam depressurization by means of pressure release valves or tubines) and process configurations that are bound to affect process energy efficiency: direct or indirect heating, percentage of condensate recovery, make-up fresh water utilization without preheating.

Computer simulation: The complete process is simulated in a water-energy oriented perspective to support a study of the interactions between the different systems and evaluate potential energy enhancing measures. As a result the energy and mass balances, and the compounds distribution within the process are obtained. The starting points for the simulation flow sheet are the process master diagram and the utility systems. The level of details required to describe specific process sections depends of their potential impact on the global energy efficiency.

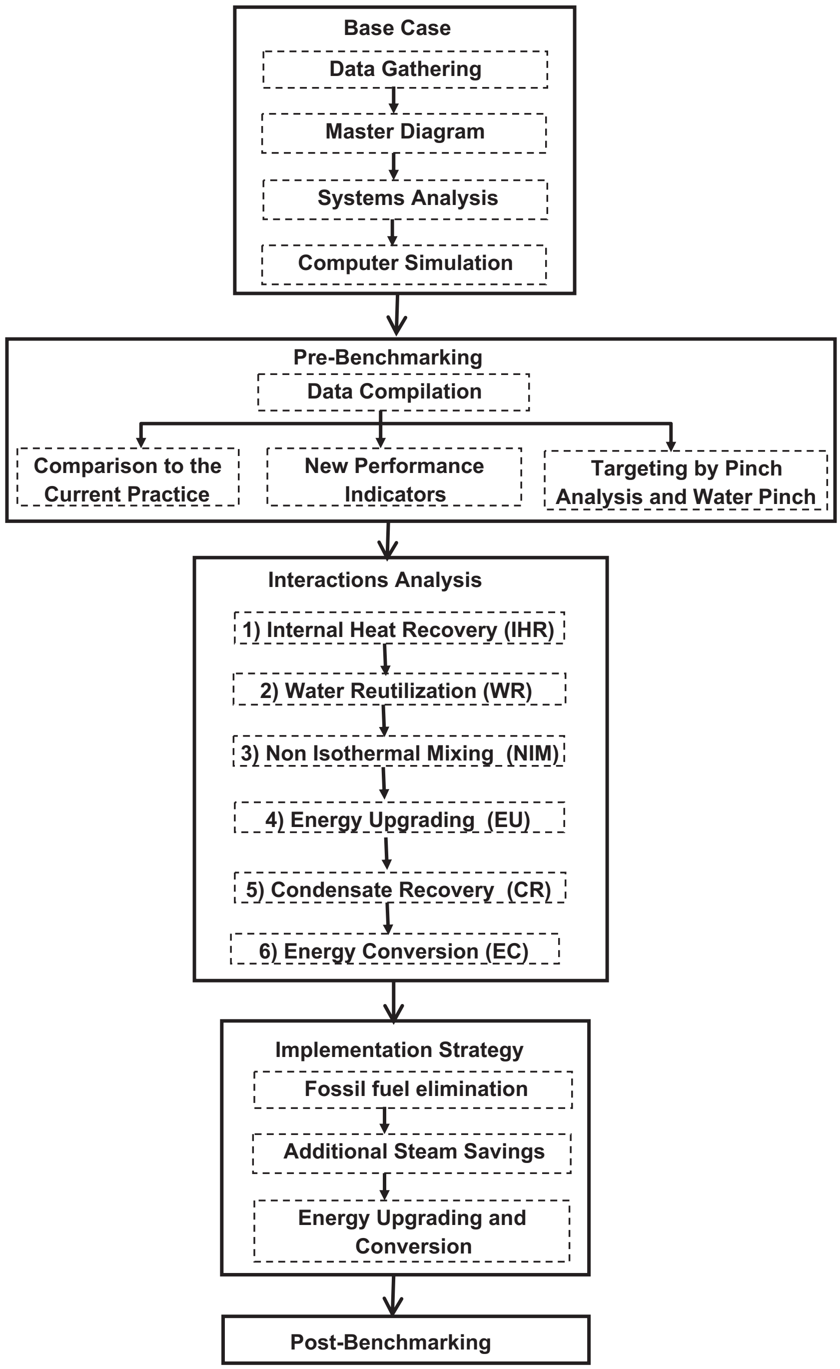

Fig. 3. Detailed unified methodology.

3.2. Stage 2: pre-benchmarking

The pre-benchmarking of the base-case has the objectives of identifying the process inefficiencies and to establish guidelines to develop effective enhancement measures. At the end of this stage, it will be possible to estimate the savings that can be obtained but the means by which they could be implemented will not yet have been identified; this will be done at the interactions analysis stage. The procedure will assist in the identification of

- unit operations with poor performance,
- maximum water reutilization and energy recovery theoretically possible and
- efficiency of the energy production and utilization.

The pre-benchmarking procedure has four steps (Fig. 3): data compilation, comparison to the current practice, computation of performance indicators, targeting by Pinch Analysis and Water Pinch. Further details on this subject can be found in Mateos-Espejel (2009).

Data compilation: All data needed to perform pre-benchmarking and to support the advanced steam and water analyses are identified. This is done in two steps: first, all sources and sinks for both heat and water are identified. Then, the initial and target temperatures, and the heat loads are collected for the streams involved in the thermal analysis. Similarly, the concentration of contaminants in the water sources, and the maximum concentrations of contaminants allowed by the water sinks are collected for the streams involved. For the thermal analysis, the required heat loads and delivery temperatures of the steam are defined. The steam utilization units and the streams involved in internal heat recovery measures are identified. So are the streams involved in non-isothermal mixing (NIM) points, including the direct injections of steam. This approach ensures that of all streams affecting the thermal balance of the process are considered. For the water analysis, all fresh water utilization units and the streams involved in water reutilization are identified. The maximum contaminant concentrations compatible with the operation of water based units are determined by the procedure recommended by Foo et al. (2006). Contaminants are components that affect the operation of the process and the quality of the product.

Comparison to the current practice: The inefficient process sections are identified by comparison to the current industrial practice. Key performance indicators (KPI) which relate variables and specific characteristics of the process are used for this purpose. For instance, steam or water consumptions of the overall process or specific sections are normalized to a unit of production. The thermal energy production is also used as an indicator of the energy transformation processes efficiency. Inefficient process sections, where improvements are most likely, are identified in this step.

New performance indicators: Performance indicators are used to quantify the savings that can be achieved before applying the energy enhancement measures. They encompass the process variables that reflect the overall thermal inefficiencies, i.e., energy and exergy contents of effluents and flue gases. Sankey diagrams of the exergy balances are constructed to quantify the exergy destroyed and lost in the production and utilization of steam. The potential of internal heat recovery, energy upgrading and power production is estimated. The exergy is used as an indicator of process inefficiencies. The indicators used in this work are defined in Table 1.

Energy indicators: The energy content of effluents and flue gases indicate the excess steam utilization by the process. Two indicators that relate the energy content of effluents (EC_E) and flue gases (EC_{FG}) to the energy supplied to the process (E_{SP}), currently produced by the boilers, are defined. Another indicator that relates the total energy requirement for water heating (EC_{WTot}) is also used.

Exergy indicators: The exergy content of a heat flow is defined as the heat load (Q) multiplied by the Carnot coefficient (η_i). The ambient temperature to be used corresponds to the winter conditions where the mill is located (4 °C). Internal heat recovery, effluents reutilization, cogeneration or heat upgrading are measures that reduce exergy lost and destroyed. The exergy destroyed represents the lost potential for energy conversion (i.e. power production). The difference between the exergy supplied to the process for steam production (Ex_{SP}) and the exergy used by the process (Ex_{Proc}) is exergy destroyed due to the difference between the temperature of utilities and the actual temperature required by the process. Thus an indicator (Ex_{EC}) relating the exergy destroyed to the total exergy supplied to the process (E_{SP}) is defined. Exergy indicators for the heat rejected are defined as the ratio between the exergy content of hot effluents (ExC_E) and flue gases (ExC_{FG}) and the exergy used by the process (Ex_{Proc}). The sum of ExC_E and ExC_E is a measure of the potential steam savings that can be achieved by internal heat recovery (ExC_T). An indicator that considers the exergy used for water heating (ExC_{WTot}) is also defined.

Targeting: The water and thermal composite curves are constructed to determine the minimum water and energy requirements as well as the maximum potential for internal heat recovery and water reutilization.

3.3. Interactions analysis

The procedure presented below is unique in that it incorporates six energy enhancing techniques in a structured manner that makes the best use of synergies and avoids counter-actions (Fig. 4). Two of those techniques modify the overall energy balance of the process; they are water reutilization and elimination of non-isothermal mixing. They will therefore interact very strongly with internal heat recovery and will modify the pinch diagram and any heat exchanger network that may have already been designed or implemented. The use of direct mixing of water for preheating and cooling also affect the possibility to save water by systems closure. Therefore, those three techniques form a triangle of intense interactions (Fig. 4). The installation of a heat pump in a process requires the connection of hot and cold streams to the device (two streams in the case of conventional recompression heat pumps, three in the case of an absorption pump). This will not modify the pinch diagram but will subtract hot and cold streams from the pool available for internal heat recovery. Those four techniques and the way they are applied in synergy determine by how much the steam and water demands of a process can be reduced. Once they have been applied, the condensates collection and return network is examined to determine if the recovery rate can be improved so

Table 1
Energy performance indicators.

Name	Definition	
Energy rejected in effluents	$EC_E = mC_{p,i}(T_i\text{-}T_{E.treat})/E_{SP}$	(1a)
Energy rejected in flue gases	$EC_{FG} = mC_{p,i}(T_i\text{-}T_{SAC})/E_{SP}$	(1b)
Energy for water heating	$EC_{WTot} = mC_{p,i}(T_i\text{-}T)/E_{SP}$	(2)
Exergy rejected in effluents and in flue gases	$ExC_E = mC_{p,i}(T_i\text{-}T_{E.treat})\eta_i/Ex_{\text{Proc}}$	(3a)
	$ExC_{FG} = mC_{p,i}(T_i\text{-}T_{SAC})\eta_i/Ex_{\text{Proc}}$	(3b)
Total exergy rejected	$ExC_T = ExC_E + ExC_{FG}$	(4)
Energy conversion	$ExC_{EC} = (Ex_{destroyed})/Ex_{SP}$	(5)
Exergy for water heating	$ExC_{WTot} = Ex_{Water}/Ex_{Proc}$	(6)

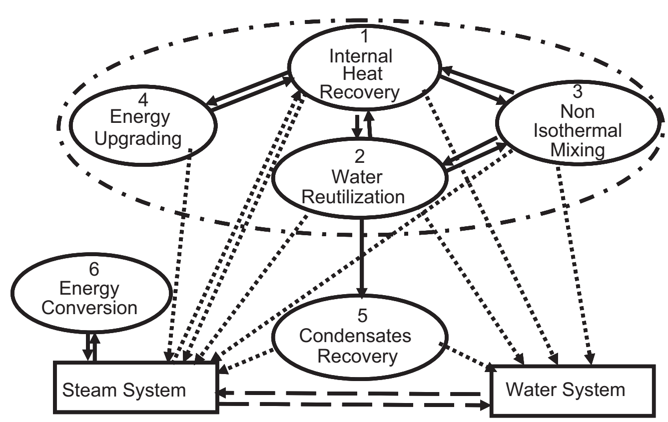

Fig. 4. Interactions analysis. The six techniques used for enhancing energy efficiency are shown.

as to reduce the water make-up required at the deareator and the steam needed to preheat the water fed to the boilers. Once all the energy enhancing measures have been applied, part of the installed steam producing capacity of the power plant may be available for non-process utilization such as power production by steam turbines.

The systems interactions that modify the process thermal balance are assessed by analyzing the changes to the thermal composite curves, to the minimum energy requirements and to the pinch point position. Performance indicators are used to quantify the improvement of the overall energy efficiency. Variations in steam and water usage are also computed. The details for each step can be found in Mateos-Espejel (2009).

Step 1: internal heat recovery

The starting point of the procedure is the process in its existing configuration. The pinch diagram for this configuration is constructed and the corresponding heat exchanger network is designed. It is compared to heat recovery measures which may have already been implemented in the mill; pinch violations are identified

Step 2: water reutilization

Water Pinch Analysis is used to identify measures for system closure. This will reduce steam consumption and it is also likely to eliminate some of the non-isothermal mixing points. The water streams which are reused in the process will modify the pinch diagram. Pinch rules violations may be eliminated but could also be created because of the pinch point modification. A new heat exchanger network is designed on the basis of the new pinch diagram.

Step 3: elimination of non-isothermal mixing

Some non-isothermal mixing points remain after systems closure. They are identified by analyzing the exergy destroyed at each point and correcting measures are developed. Some of these measures will consist of substituting internal heat recovery to streams mixing and will therefore modify the heat exchanger network. As these measures also affect the pinch diagram a new network will be developed.

Step 4: energy upgrading

Implementation of heat pumps in a process can be an efficient way to reduce the heating and cooling requirements. However, since the investment cost is substantial, it should be performed after internal heat recovery has been maximized. The positioning of these devices must take into account the pinch point. The heat upgraded must come from a hot stream below the pinch and the heat receptor must be a cold stream above it. The absorption–desorption cycle is driven by a hot stream above the pinch or by the utilization of utility steam (Bakhtiari et al., 2007). A limiting factor is often the temperature lift required to match the heat pump internal requirements in heat loads and the available heat sinks and sources. The best option for implementing an AHP would require either the heat source or receptor to be close to the pinch point. The temperature lift can be reduced by rearrangement of the HEN, thus producing a new configuration.

Step 5: condensate recovery

After steam savings are maximized by the previous techniques, the condensates that can be recovered are identified as well as the steam injections that can be replaced by heat exchangers. These measures reduce the steam consumption in the deareator.

Step 6: energy conversion

A combined process and utility analysis is performed to adjust the steam pressure levels to the temperature profile of the process. The objective is to compute the proper size and type of turbines, required for the amount of steam available for power production.

3.4. Implementation strategy and post-benchmarking

As the existing process configuration and operating conditions vary from process to process, a strategy for the implementation of energy enhancement programs in the most advantageous way for each case is proposed. The optimum order of implementation may be different from the order in which the systems interactions have been analyzed. Economic factors are predominant in the formulation of the strategy.

The simple payback time (PBT) is used as the economic indicator

$$PBT = I/[(R+S)\text{-}OC] \tag{7}$$

The investment costs are computed by the usual pre-engineering method based on the cost of bare module (CBM) and multiplying factors (Ulrich and Vasudevan, 2004). These bare module cost vary depending on the equipment type, its size and construction material. The bare module includes all direct and indirect expenses. The total cost of installed and commissioned equipment is obtained by multiplying its purchasing price by factors, which represent the fractional contributions of the various cost components

- Bare module: $CBM_{steel}=3.18$; $CBM_{Ti}=11.2$
- Contingency and fee: $CTM=1.18\times CBM$
- Auxiliary facilities costs (site development, off-site facilities): $CGR=1.3\times CTM$

A post-benchmarking analysis is done at the end of the retrofit project to quantify the improvement of the energy efficiency. The performance indicators are computed again after all energy enhancing measures have been implemented.

4. Case study

The Kraft mill used in this study has an average production of 700 adt/d (adt = air dried ton) of high grade bleached pulp. It is part of an eco-industrial cluster in which, in addition to pulp production, steam is exported to a nearby sawmill, the municipal waste from the adjacent town is treated at the mill site, forest biomass is used as fuel to produce steam and district heating is under study.

The mill uses eight batch digesters that operate in parallel for chemical delignification and a five stage bleaching sequence which utilizes different bleaching agents (ClO_2, H_2O_2, NaOH) at different conditions. The weak black liquor (BL) concentration (15% solids concentration) is performed in three steps; first, the BL is passed through a set of pre-evaporators (19% solids) driven by recycled steam, and then it is sent to two parallel trains (55% solids) with post-concentrators (70% solids) driven by live steam. Drying is performed in two steps: first, the pulp is passed over rotating cylinders where steam is condensed and then, hot air is used to attain the final specification of pulp consistency. The mill management is planning to replace the current biomass boiler which is old and has a low efficiency (43%) by a new boiler. In addition the mill is under negotiation with regional power company to install a cogeneration unit to produce and sell 35 MW of electricity. The retrofit project proposed below will incorporate those plans.

4.1. Stage 1: base-case

4.1.1. Data gathering

There are two principal sources of information available in this study: archived measured values for different years (2002–2003 and 2005 for steam; 2006 for water) and the PIDs. A low and very tolerable discrepancy of 4% was found between data on steam production and on steam consumption. This difference is within the range of process variability. The high cost of steam may have been a reason to maintain good monitoring of all steam using operations. The same procedure was applied to the water system where a difference of 31% between water intake and consumption was observed. This large difference is due to poor monitoring of water usage perhaps tolerated because of its low cost. However, the water utilization is strongly related to steam consumption making it also part of the energy bill.

4.1.2. Master diagram

Fig. 5 gives an overview of the master diagram of the process indicating the number of available PIDs from which each section was developed. The process has been divided into three major parts to address the objective of the study: the steam system, the water system, and the pulp manufacturing process itself. The inputs to the process are the wood chips, water, chemicals for bleaching, the purchased fuel, and the municipal effluent treated by the mill. The outputs are bleached pulp, steam for sale to the sawmill, flue gases from the boilers, water returned to the environment and sludge from the treatment plant.

4.1.3. Steam system analysis

The steam required by the mill (Fig. 6), is supplied by four boilers that generate high pressure steam ($HP=3100$ kPa, $T=371$ °C): two spent liquor recovery boilers (RB), a biomass boiler (Bi) and a small fossil fuel boiler (FF). Medium ($MP=965$ kPa, $T=179$ °C) and low pressure ($LP=345$ kPa, $T=143.5$ °C) steam are produced through desuperheating and depressurization of HP steam in pressure reduction valves. Depressurization of HP and MP steam in release valves reduces the potential for electricity generation. Part of the clean condensate produced in the process is recovered and mixed with make-up water at the deareator. Table 2 gives the steam consumption by process section for winter conditions. The steam consumption is reduced by 10% during the summer. Fossil fuel is partly used to compensate for the poor performance of the boilers; however it should only be used to absorb the fluctuations of pulp production and seasonal variations of the steam demand. A Kraft process could in principle be energetically self-sufficient (McIlroy and Wilczinsky, 1999). The utilization of fossil fuel for steam production in the process is a sign of poor energetic performance. Major inefficiency sources have been identified on the process side:

- Non-isothermal mixing such as direct injections of steam in the deareator.
- Low condensate recovery rate of 43% as compared to the typical Canadian average of 60%.

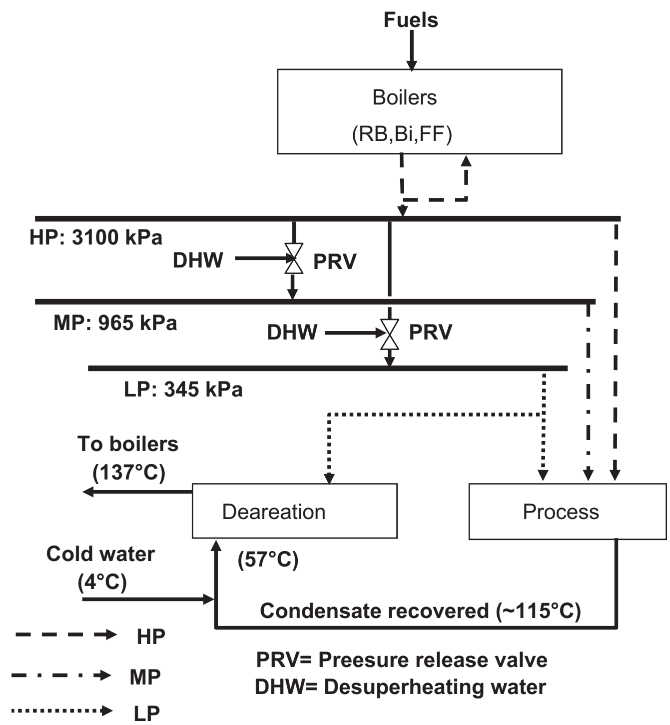

Fig. 6. Steam production (Mateos-Espejel, 2009).

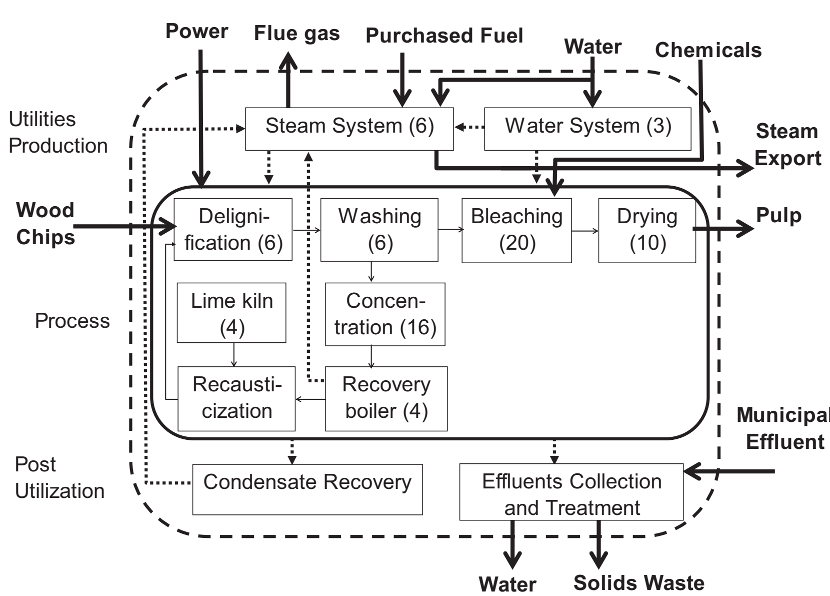

Fig. 5. Overview of the master diagram. The number of PIDs available for each section is indicated.

Table 2
Steam consumption by process section.

Process section	GJ/adt	MW
Delignification	3.99	32.4
Bleaching	1.75	12.5
Concentration	4.2	14.2
Drying	4.76	34.2
Water heating	1.54	38.6
Recaustification	0.57	4.7
Deareation	2.66	8.2
Steam export	0.69	21.6
Boilers, and other equip.	0.98	5.6
Total process consumption	**21.14**	**172**

- Low efficiencies of the recovery boilers (58%) and of the biomass boiler (43%), below the typical Canadian average of 65%. The reason for the low values is principally the old age of the equipment. The efficiency (Eq. (7)) is computed as the ratio between the energy consumed for HP steam production and the high heating value of the fuel multiplied by its mass flow

$$\eta = \frac{\dot{m}^v (h_{out} - h_{in})}{\sum_i \dot{m}_i^f HHV_i} \tag{7}$$

4.1.4. Water system analysis

An analysis of all water streams and a comparison to the current practices for each process section were used to obtain the necessary data to fill the gaps in the water balance of the measured data. Data reconciliation was performed to generate a reliable set of data by the software Aspen Water. The reconciled data encompass 94% of the feed water to the process. Savulescu and Alva-Argaez (2008) reported a percentage of 90 in a similar study.

The water used in the process undergoes two pre-treatments before being utilized: during summer, the period of highest water consumption, 65% of the feed water, referred to as treated water, is screened and demineralized for steam production and for utilization in sections where it is in direct contact with the pulp. Those sections are pulp washing, pulp bleaching, pulp drying and the ClO_2 making plant. The remaining 35% of the feed water is only screened (screened water) and is used for cooling, vent gases scrubbing and housekeeping. Table 3 gives the water consumption by process section. The consumption of screened water varies appreciably between summer and winter. A large amount of chilled water is required for the ClO_2 making plant during the summer with the current equipment (absorption chiller and steam ejector). The overall water consumption increases by 18% during summer.

The treated water is used at 5 temperature levels (Fig. 7): cold (winter: 4 °C, summer: 20 °C), warm (44 °C), and hot (58, 62 and 71 °C). The warm water is generated in the condensers of the black liquor evaporation section. Hot water at 58 °C is produced by indirect heat exchange with the effluents from the evaporation 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 by direct steam injection in the hot water tank. Part of the water at 62 °C is directly used and the rest is heated to 71 °C by indirect heat exchange with steam.

There are several sources of inefficiencies in the water system:

- Non-isothermal mixing such as direct injection of steam in the hot water tank, and the mixing of streams at different temperature levels in the warm water tank.

Table 3
Water consumption by process section.

Process section	m^3/adt	m^3/h
Treated water		
Delignification and washing	10.1	295.7
Bleaching	30.7	896.6
Concentration	1.0	28.2
Drying	10.7	312
Recaustification	2.0	58.6
Deareation	4.8	138.7
Steam export	0.0	-
Boilers	0.2	4.4
Non-process uses	4.6	134.0
Screened water		
Bleaching	24	700.6
Recaustification	4.6	132.8
Non-process uses	11.1	323.8
Unaccounted water	6.4	186.9
Total process consumption	**110.1**	**3212.2**

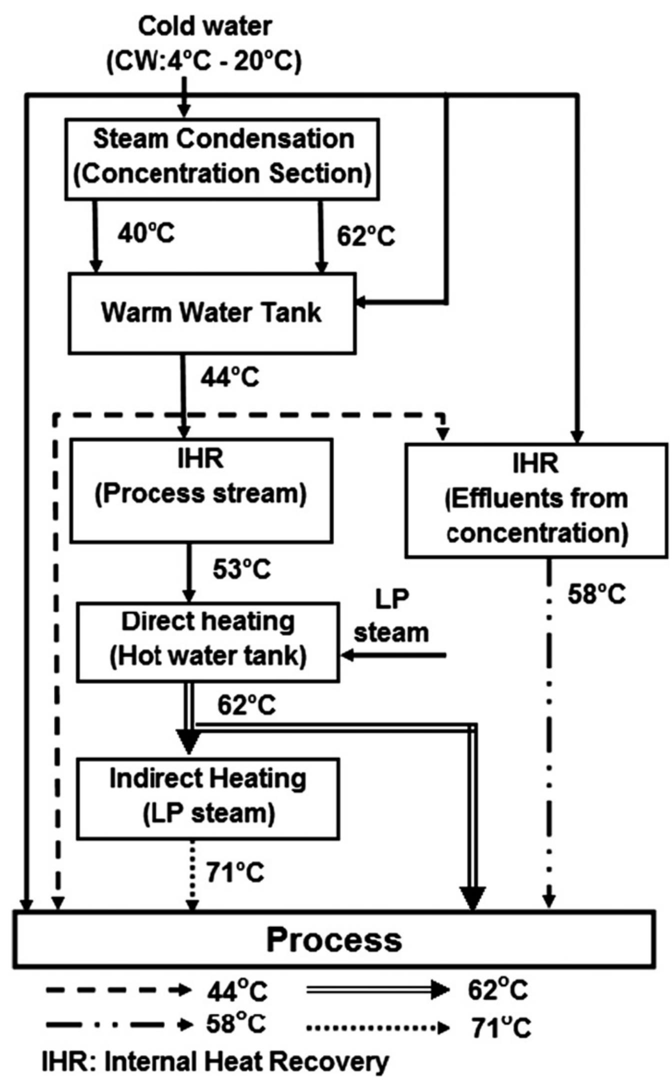

Fig. 7. Water production (Mateos-Espejel, 2009).

- The effluents from the evaporation section generally have a low contamination level (Sankari et al., 2004) and they can be reused in other sections of the process. This reutilization can save water and steam for hot water production, since the temperature of the evaporation effluents is almost 70 °C.

4.2. Computer simulation

CADSIM Plus has been used for this purpose. It is a simulator specialized in pulp and paper processes, broadly used in Canada. The unit operations were simulated as water and steam consumers. Sections, such as bleaching, drying, black liquor evaporation and the recovery boilers that affect directly steam and water consumption were modeled in detail. Simplified models were used for recausticization and lime kiln because these sections are not large steam consumers. 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 is not necessary as its impact on the energy balance is negligible. An excel spreadsheet was used to transfer values to the simulation (T, P, flowrates), and to extract data for subsequent analyses.

The simulation has been validated by a comparison between simulated and measured data. In the case of the steam, the difference is 0.9%, and in the case of water it is 6%. Tables 4 and 5 show the overall steam and water balances obtained from the simulation.

The simulation can be used to analyze possible changes on operating conditions or the implementation of energy efficiency measures. Several process inefficiencies have been identified and should be eliminated by the application of energy enhancing techniques.

4.3. Pre-benchmarking

All steam and water users have been identified after the characterization of both utilities systems. The utilization of make-up water without preheating and direct injection of steam has been found in the hot water production and condensate recovery. Internal heat recovery measures have already been implemented by the mill to heat water (Fig. 7) as well as water reutilization strategies within the bleaching section. Thirty cold streams and 30 hot streams have been identified.

Eighteen water sources and 19 water sinks have been identified. Some water streams are also common with the steam network (process effluents and hot water requirements). The fact that some streams are involved in both steam and water analysis underscores the importance of systems interactions. An exhaustive list of the streams used in this study can be found in Mateos-Espejel (2009).

The concentration of dissolved solids (DSC), which include organic and inorganic by-products from the chemical delignification of wood, is a constraint to be taken into account when designing water reutilization measures. The concentration of dissolved solids is an appropriate parameter to classify the water steams. Other contaminants contained in some water sources may also be accounted for (i.e. methanol in the evaporators fouled condensates) before reusing them.

4.3.1. Comparison to current practice

An energy survey conducted at 49 Pulp and Paper mills (Francis et al., 2006). This sample includes 47 Canadian mills, 24 of which are Kraft processes, and 2 from the United States. The Canadian average was used because the performance of the mill as is, does not meet those benchmarks. The steam consumption (21.14 GJ/adt) is above the average (18.48 GJ/adt). The delignification, the BL evaporation and the pulp bleaching sections are also above the average. The net thermal deficit, i.e. the difference between the steam produced by recovery boilers and used by the process, is 8.1 GJ/adt which is above the Canadian average of 2.4 GJ/adt.

In terms of water usage and effluent production, the data used for comparison were taken from the average Canadian consumption in the 1990s given by Turner (1994), which is still representative of the situation in Canada. The overall water consumption (110.1 m^3/adt) is clearly above the average (75 m^3/adt). The effluents produced by the black liquor evaporation (15.8 m^3/adt) and bleaching (58.6 m^3/adt) sections are also above the average of 4.6 and 48.5 m^3/adt, respectively. The overall water and energy performances of the mill are above the typical Canadian averages.

4.3.2. New performance indicators

The energy and exergy content indicators are presented in Table 6. The Sankey diagram of the exergy flows is shown in Fig. 8.

- *Flow 1*: Total exergy obtained by the combustion of fuels (heat content)
- *Flow 2*: Destroyed exergy by the temperature difference between the gases of combustion and the required temperature for the production of HP steam.

Table 4
Overall water balance.

Water inputs		**Effluents**	
Section	**m^3/h**	**Section**	**m^3/h**
Water IN wood chips	46.3	Water OUT pulp	2.0
Water intake	2909.1	Effluents	3100.1
Direct steam injections	69.9	Water evaporated	52.6
Unaccounted	186.9	Condensate to the sewer	49.1
		Export	8.4
Total	**3212.2**	**Total**	**3212.2**

Table 5
Overall steam balance.

Steam production		**Condensates**	
Section	**t/h**	**Section**	**t/h**
HP produced by the boilers	236.8	Condensate recovered	109.9
Desuperheating	35.8	Steam injections	69.9
		Deareation	35.3
		Condensate to sewer	49.1
		Export	8.4
Total	**272.6**	**Total**	**272.6**

Table 6
Energy and exergy data for the nominal process.

	Energy content (MW)	***Exergy content (MW)***
Fuels combustion	183.8	125.5
Flue gases	11.8	4
From fuel combustion to steam (E_{SP}, Ex_{SP})	172	121.5
HP steam production	172	78
Steam utilization	172	62.8
Process consumption (Ex_{Proc})	172	47
Hot effluents	44.9	7.3
Water heating (Ex_{WTot})	37.1	12.2

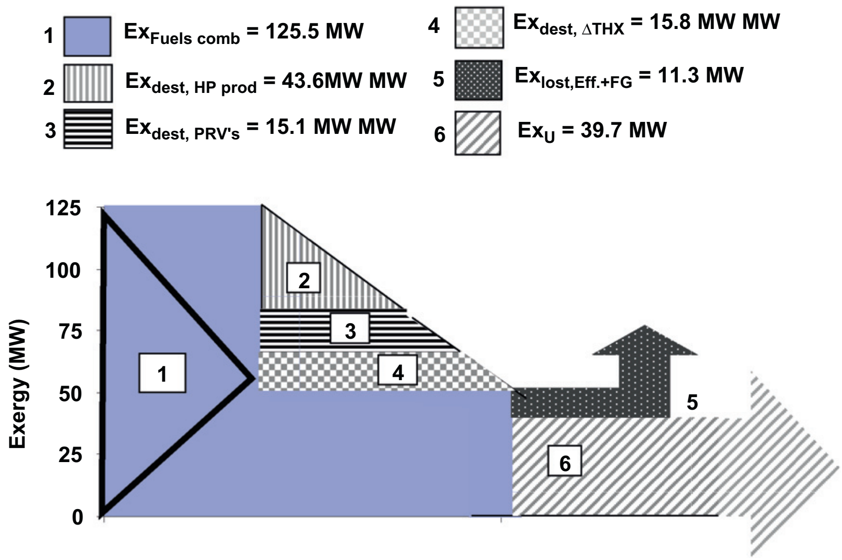

Fig. 8. Sankey diagram of the exergy flows supplied to the process.

Table 7
Exergy and energy indicators for the nominal process.

	Energy indicators (MJ/MJ)	*Exergy indicators (MJ/MJ)*
Flue gases	$EC_{FG}=0.07$	$ExC_{FG}=0.09$
Hot effluents	$EC_{E}=0.26$	$ExC_{E}=0.16$
Total savings	$EC_{T}=0.33$	$ExC_{T}=0.25$
Energy conversion		$ExC_{EC}=0.61$
Water heating	$EC_{WTot}=0.22$	$ExW_{Tot}=0.26$

- *Flow 3*: Destroyed exergy by adiabatic expansion in the PRV's for the production of MP and LP steam.
- *Flow 4*: Destroyed exergy by temperature difference between live steam and the process heat sinks.
- *Flow 5*: Exergy lost with the hot effluents and flue gases.
- *Flow 6*: Useful exergy supplied to the process.

The actual exergy consumed by the process ($Ex_{Proc}=47$ MW) is the difference between the total exergy brought in by the by fuels (flow 1) and, the sum of the exergy destroyed (flows 2–4) and the exergy lost with the flue gases. The exergy outputs are the exergy lost (flow 5) and the useful exergy (flow 6).

The energy supplied to the process by the combustion of fuels, for steam production, is invariant until it is consumed by the process, whereas exergy is destroyed along the same path (Table 6). This highlights the usefulness of considering exergy in the analysis. The indicators are shown in Table 7. About 61% of the exergy supplied by fuels (ExC_{EC}) is destroyed. This represents a high potential for energy conversion that is untapped. The destruction of exergy in heat exchangers cannot be eliminated but could be significantly reduced by the adjustment of the steam pressure levels and the improvement of the boilers efficiency. The latter subject has not been investigated in this work. The implementation of turbines would eliminate the destruction of exergy in the PRVs.

The possibility of improvement by internal heat recovery or energy upgrading accounts for 25% (ExC_T) of the current exergy required by the process (Ex_{Proc}). The high temperature of the flue gases makes their exergy content (ExC_{FG}) higher than their energy content (EC_{FG}). In contrast, the exergy content of effluents (ExC_E) is lower than their energy content (EC_E) because of their near

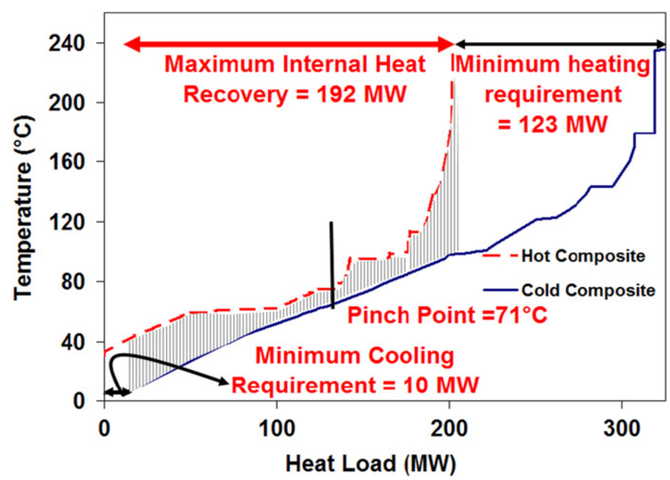

Fig. 9. Thermal composite curves of the process.

ambient temperature. About 20% of the energy used by the process is employed for water heating (EC_{WTot}).

4.3.3. Targeting by pinch analysis

Following an analysis of the variation of the heating requirement for a ΔT_{min} of 10 °C to construct the composite curves. This value has also been used in previous Pulp and Paper studies (Savulescu and Alva-Argaez, 2008). The composite curves for the process are shown in Fig. 9. A minimum heating requirement (MHR) of 123 MW, a minimum cooling requirement (MCR) of 10 MW and a pinch point (PP) of 71 °C were obtained. The MHR suggest that the steam consumption of the process (172 MW) could be theoretically reduced by 49 MW, 29% of the current requirement. Additional savings could be obtained by upgrading the energy of the heat rejected by means of absorption heat pumps, after maximizing internal heat recovery.

4.3.4. Targeting by water pinch

The water composite curves are shown in Fig. 10. The minimum water requirement (MWR) is 1000 m^3/h, the minimum effluent production (MEP) is 880 m^3/h, the maximum water reutilization is 1360 m^3/h and the pinch point is found at $DSC=0$ ppm, i.e. for pure water. These targets suggest that the

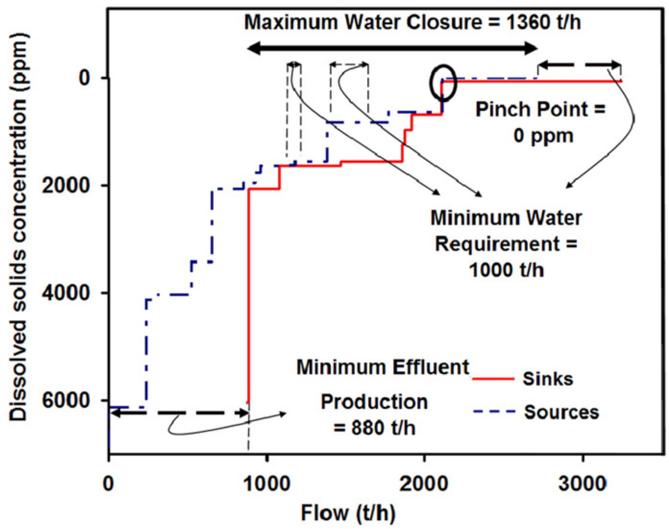

Fig. 10. Water composite curves of the process.

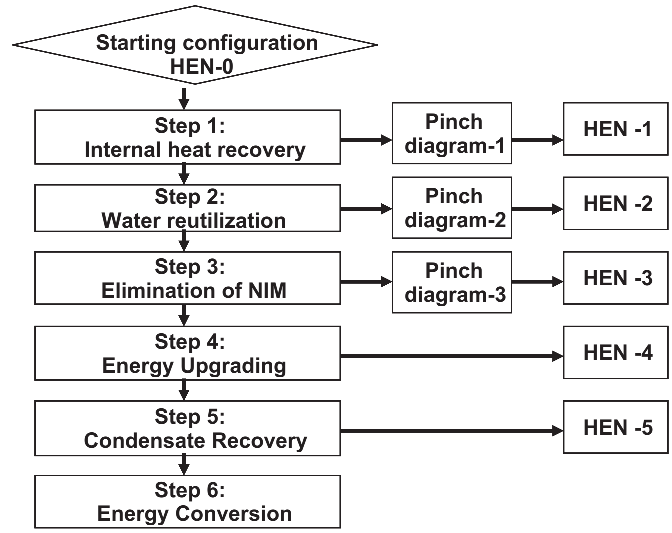

Fig. 11. Interactions analysis procedure. The six steps are shown with the respective pinch diagram and heat exchanger network. The variation of the pinch diagram is a result of change is the process thermal balance after the energy enhancing technique is employed.

overall water consumption could theoretically be reduced by 31%, which would decrease the steam utilization for water heating. Additional savings would require the implementation of external water purification devices.

4.3.5. Synthesis

The steam and water consumptions are above the average industrial practice. The black liquor evaporation and pulp bleaching sections are the most inefficient. The amount of exergy lost with effluents and flue gases (25% of the exergy supplied) is caused by the lack of internal heat recovery and water reutilization. The side effects of these inefficiencies are observed in the total amount of destroyed exergy (61% of the exergy supplied) and the above average net thermal deficit (8.1 GJ/adt). Targeting establishes the maximum savings of steam (29%) and water (31%) that can be achieved by internal heat recovery and water reutilization. However, as some streams are part of both the water and energy systems, their interactions should be identified before measures are proposed. Water reutilization projects will reduce the steam utilization since water heating represents a full 22% of the total steam consumption. All these issues are interrelated and cannot be tackled individually. An interaction analysis which considers all the inefficiencies encountered during the base-case characterization is performed in the next section.

4.4. Interactions analysis

The cases developed in each step are presented in Fig. 11. The modifications to the composite curves and the results for the cases developed are shown in Fig. 15 and Table 8.

4.4.1. Step I: internal heat recovery

The violations of the pinch rules in the current process configuration are:

- Utilization of a hot stream above the pinch point to heat a cold stream below (12.5 MW).
- Utilization of a hot utility to heat a cold stream below the pinch point (22.2 MW).
- Utilization of a cold utility to cool a hot stream above the pinch point (14.3 MW).

A retrofit heat exchanger network (HEN-1 in Table 8) has been developed based on the current process temperature profile

Table 8
HEN performances.

	Steam savings (MW)	Surface area (m^2)	EC_E
HEN-0	–	–	0.26
HEN-1	22.5	3580	0.20
HEN-2	29.7	2120	0.18
HEN-3	38.1	2990	0.13
HEN-4	43.7	5130	0.09
HEN-5	46	5350	0.09

(Fig. 9). The increased utilization of heat from effluents, results in a reduction of rejected heat (EC_E). Heat recovery above the pinch from flue gases is an option to be privileged because of their high exergy content. As the available heat from the flue gases is recovered their energy content indicator has a value of zero.

4.4.2. Step II: water reutilization

Measures to decrease the water consumption by reusing different process effluents have been proposed and detailed in Mateos-Espejel et al. (2008). The implementation of these measures reduces the steam demand by 15.1 MW prior to internal heat recovery. These savings are achieved through reduced hot water production and reuse of streams that have a higher temperature than the water currently used. The effects on the thermal composite curves and the MER after water reutilization are shown in Fig. 15a. The violations to the pinch rules after water reutilization are:

- Utilization of a hot stream above the pinch point to heat a cold stream below it (15.2 MW).
- Utilization of a hot utility to heat a cold stream below the pinch point (3.0 MW).
- Utilization of a cold utility to cool a hot stream above the pinch point (19.2 MW).

A new heat exchanger network (HEN-2) is developed for the modified process. The steam savings achieved by the water reduction measures have been included in the results shown in Table 8. By applying Step II, the steam savings increase to

29.7 MW which is larger than after Step I. Furthermore, less surface area is required by HEN-2. The reduction of the rejected heat in the effluents (EC_E) comes from their reutilization and the increased heat recovery below the pinch.

4.4.3. Step III: elimination of non-isothermal mixing

Inefficient non-isothermal mixing points in the water and steam systems have been identified by Mateos-Espejel (2009). After water reutilization mixing points are eliminated because make-up water and steam injection are no longer required in the warm and hot water tanks (Fig. 7). The exergy destroyed associated with the mixing of the condensate recovered with cold make-up water ($Ex_{destroyed}$=1 MW) and the steam injection in the deareator ($Ex_{destroyed}$=1.5 MW) are the most inefficient non-isothermal mixing points left (Fig. 12a) after water reutilization is implemented. The way to eliminate these inefficiencies is shown in Fig. 12b. The fresh water should be preheated to 137 °C by means of a process stream before it is mixed with the condensate recovered. The new heat exchanger must operate at 350 kPa. It is also assumed that the condensate tank and the deareator can support this pressure. These measures modify the composite curves (Fig. 15b), and thus the corresponding HEN. HEN-3 makes a better usage of the low temperature energy below the pinch where the effluents energy content indicator is reduced from 0.18 to 0.13. The steam savings are increased by 8.4 MW but the exchange area is also increased from 2120 to 2990 m^2. The elimination of non-isothermal mixing shifts the energy demands from high (steam) to low temperature heat sources (effluents). Therefore, the steam savings achieved by internal heat recovery are increased.

4.4.4. Step IV: energy upgrading

A new network is created to permit the efficient implementation of absorption heat pumps. The sections above the pinch point of HEN-3 and HEN-4 are shown in Figs. 13 and 14. The surface area required for HEN-4 is larger than in the previous cases because the $\Delta T_{approach}$ of the process to process heat exchangers is reduced. The heat loads of the streams close to the pinch have been made available for the implementation of absorption heat pumps. These options become interesting when power production is also part of the process retrofit because the more steam is saved, the more steam can be used for power production.

Two absorption heat pumps can be integrated in the process. One uses MP steam to upgrade the heat from the bleaching effluents. This AHP reduces the heating demand (2 MW) for black liquor evaporation and in the deareator. Another AHP driven by MP steam can be placed to recover the heat rejected in the production of chilled water during the summer. The steam demand of the process is reduced in the deareator as well as for hot water production and white-water (aqueous suspension of fine fibers entrained as water is drained from the pulp before drying) heating by a load of 3.6 MW. In addition, fresh water intake is reduced by 540 m^3/h.

4.4.5. Step V: condensate recovery

Two measures have been identified to increase condensate recovery: the replacement of steam injection used to heat white-water by a heat exchanger and collection of the condensates produced in the recausticization unit. A reduction of the steam consumption for deareation (2.3 MW) is achieved because less cold make-up water is needed.

4.4.6. Step VI: energy conversion

Mateos-Espejel (2009) has proposed that the steam pressure levels be adjusted to improve the fit to the temperature profile of the process. They also estimated the size of the new biomass boiler (116 t/h of steam) to produce 35 MW of electricity that is to respect the strategic plan of the mill. The pressure of the steam produced was also increased to 8800 kPa to generate the power required. Cakembergh-Mas et al. (2010) analyzed the replacement of the pressure release valves by a cogeneration unit in this process. A back pressure turbine driven by HP (3100 kPa) produced by the recovery boilers and a condensing turbine driven by VHP (8800 kPa) produced by the new biomass boiler were recommended.

4.4.7. Results

The pinch point is lowered to 57 °C after water reutilization. The minimum cooling requirement increases because less water needs to be heated. As a result, part of the cold water used for steam condensation in the black liquor evaporation section becomes an additional cooling demand for the overall process. The modification to the minimum energetic requirement after

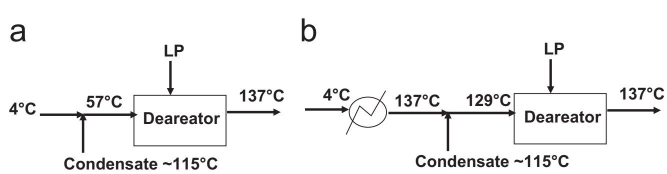

Fig. 12. (a) Current deareator system and (b) retrofit system. Modification to eliminate the NIM point at the input of the deareator.

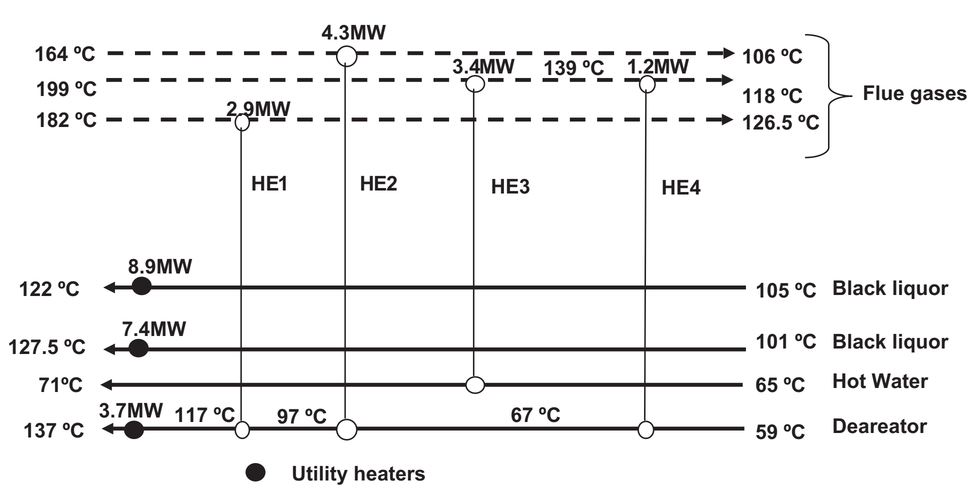

Fig. 13. HEN-3: network design above the pinch (Mateos-Espejel, 2009).

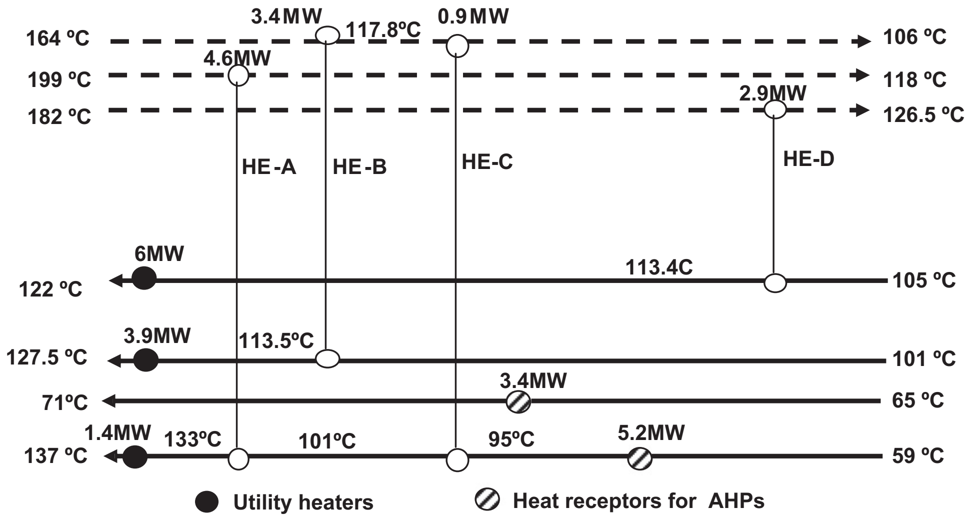

Fig. 14. HEN-4: network design above the pinch (Mateos-Espejel, 2009).

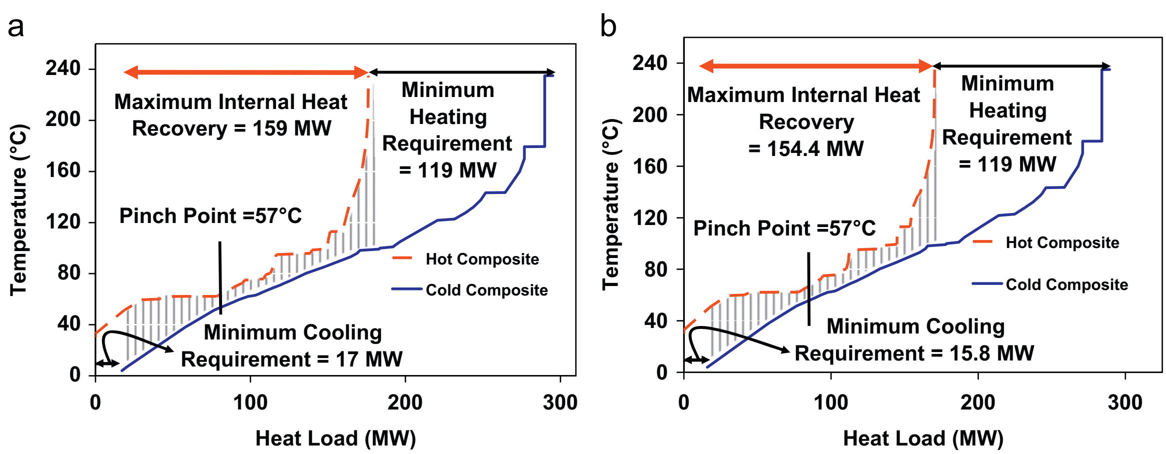

Fig. 15. (a) Pinch diagram 2 and (b) Pinch diagram 3. Pinch diagram 2 after implementation of water reutilization; Pinch diagram 3 after elimination of NIM points.

eliminating non-isothermal mixing shifts some of the energy demands from above the pinch to below.

The optimal HEN uses the heat content from the flue gases because their high temperature makes them suitable to heat cold streams above the pinch point. However, the most important steam savings come from recovery of available heat below the pinch causing a reduction of the rejected heat in the effluents (EC_E). The implementation of water reduction measures increases the steam savings and reduces the required heat exchange surface area. The reason is a reduction of the energy required by the process and of the maximum internal heat recovery (Fig. 15b). The elimination of non-isothermal mixing also has a positive effect on the steam consumption savings but at a cost in heat exchange surface required. The surface area required by, HEN to implement an absorption heat pump increases significantly (+2230 m^2) because the temperature approach ($\Delta T_{approach}$) for the exchangers used above the pinch is reduced. The area of the HEN also increases by the replacement of steam injection above the pinch by heat exchangers to increase the condensate recovery rate and thus reduce the steam needed by the deareator. The design of a cogeneration system considers the production and utilization of steam in the process. Therefore, the turbines are implemented after all steam measures have been accomplished and the size and pressure of the new biomass boiler are determined.

The last stage of the methodology is the development of a strategy for the implementation of energy saving measures that take into account economic factors and technical constraints.

4.5. Implementation strategy

A three-phase strategy has been proposed (Fig. 16). All prices are in 2008 Canadian dollars. The cost of the steam, provided by the mill staff, is 37.5 \$/t when it is produced by a fossil fuel boiler and 3.3 \$/t when produced by a biomass boiler. The cost of fresh water is 0.065 \$/m^3 and the cost of effluent treatment 0.1 \$/m^3 (Lovelady and El-Halwagi, 2007). The price of electricity sold to the grid is 90 \$/MWh (Cakembergh-Mas et al., 2010). The operating time of the mill is 8400 h/a.

4.5.1. Phase I: base steam demand reduction and shutdown of the fossil fuel boiler

The average and the yearly maximum utilization of steam were computed (Table 9 and 10). The objective of Phase I is to reduce the steam demand by 24.7 MW so that the bunker oil boiler may be permanently shutdown.

Condensate recovery and water reutilization are the main techniques applied in this phase. The measures (1–2) for increasing the condensate recovery rate are implemented first because they do not affect any part of the process other than the deareator. The implementation of water reduction measures (3–6) modifies the energy balance of the mill. Thus all these measures have been implemented before eliminating non-isothermal mixing (7). The proposed measures are:

1. Replacement of steam injection by a heat exchanger for white-water heating.
2. Condensate recovery in the recausticization section.
3. Reutilization of the effluents from the black liquor evaporation section, in the pulp washing and in the recausticization sections.
4. Reutilization of white-water in the bleaching section.
5. Increased reutilization of filtrate within the bleaching section.
6. Reutilization of the sealing water of the vacuum pumps.
7. Preheating of the fresh water before the deareator. The heat sources used are the bleaching effluents and flue gases.

The cost of water reutilization measures is mostly associated with the installation of pumps, pipes and instrumentation. A hot oil recirculation system (Mostajeran-Goortani et al., 2009), in which the oil is used as energy carrier from the flue gases to the process streams, is required to implement all internal heat recovery measures (including measure seven).

Shutting down the fossil fuel boiler is an attractive option for the mill because the high price of this fuel makes the overall PBT (0.7 a) of Phase I quite short. The steam savings exceed the maximum bunker oil utilization, therefore biomass is also saved (5.4 MW) by the internal heat recovery measures. The cost of the hot oil recirculation system has also been included.

The implementation of Phase I alone improves significantly the energy efficiency of the mill. Additional measures would save biomass, which is less expensive than fossil fuel; however, these options could liberate steam capacity for cogeneration and generate extra revenues which would compensate for the additional investment.

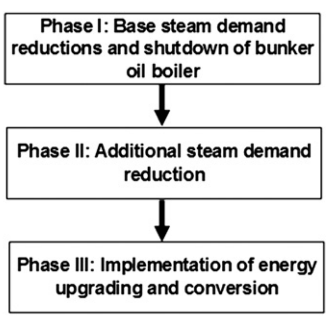

Fig. 16. Implementation methodology.

4.5.2. *Phase II: additional steam demand reductions*

The balance of the internal heat recovery measures are implemented in this phase.

1. Preheating of white-water by the bleaching effluents.
2. Black liquor evaporation by the utilization of flue gases.

They account for 10.4 MW of steam savings (0.5 M$/a), with a required investment of 4.2 M$ and a PBT of 8.4 a.

Phase II is expensive as a result of high investment and the current low price of biomass. However, as a prerequisite to increased cogeneration capacity, it is fully justified as will be shown in Phase III. Mateos-Espejel (2009) has shown that the production of electricity is more profitable than just reducing the consumption of biomass fuel. As the price of biomass is likely to rise due to an increase demand for biofuels and other bioproducts, the PBT will decrease.

4.5.3. *Phase III: energy upgrading and conversion*

Bakhtiari et al. (2009) proposed the implementation of two absorption heat pumps. They have been used to upgrade the heat of effluents that has not been used for internal heat recovery, such as:

1. Bleaching effluents to reduce the steam consumed for water and white-water heating and, by the deareator.
2. Chemical preparation section effluents during summer to reduce the cooling demand as well as the steam consumed by the deareator and the BL evaporation section.

The energy conversion measures are:

1. Reduction of LP steam from 345 to 220 kPa.
2. Reduction of the pressure of the steam used for drying (from HP to LP) and for BL evaporation (from MP to LP).
3. Implementation of two turbines (condensing and back pressure), after all steam savings have been achieved.

The implementation of the AHPs is expensive and with a long PBT (Table 11) because biomass is, for the time being, a very inexpensive fuel. The operating cost of cogeneration (12.7 M$/a) is the cost of steam produced from biomass and used only for power production. Since the mill will have to replace the current biomass boiler which has a low efficiency by a new boiler, independently of the retrofit project, the cost of a new boiler at constant capacity (65 t/h of HP steam) is not included in the

Table 9
Average and maximum utilization of steam.

Fuel used	Maximum		Average	
	MW	GJ/adt	MW	GJ/adt
Spent liquor	106.3	13.1	103.4	12.8
Biomass fuel	47.4	5.9	42.4	5.2
Fossil fuel	24.7	3.0	14.8	1.8
Total	**178.4**	**22.0**	**160.6**	**19.8**

Table 10
Phase I economic analysis.

	Steam saved (MW)	Water saved (m^3/h)	Inv. (M$)	Savings (M$/a)	PBT (a)
Condensate recovery	2.3		0.25	1.2	0.2
Water reutilization	15.1	540	1.4	8.7	0.2
Internal heat recovery	12.7		7	3.2	2.2
Total Phase I	**30.1**	**540**	**8.65**	**13.1**	**0.7**

Table 11
Phase III economic analysis.

	Steam saved (MW)	Water saved (m^3/h)	Power (MW)	Inv. (M$)	Sav. and rev. (M$/a)	Operat. cost (M$/a)	PBT (a)
Energy upgrading	5.6	540	–	4.3	0.6	–	7.0
Energy conversion	–		35	18.9	26.6	12.7	1.4
Total Phase III	**5.6**	**540**	**35**	**23.2**	**27.2**	**12.7**	**1.6**

Table 12
Economics of the full strategy implementation.

	Steam saved (MW)	Water saved (m^3/h)	Power (MW)	Inv. (M$)	Profits (M$/a)[a]	PBT (a)
Phase I	30.1	540		8.65	13.1	0.7
Phase II	10.4			4.2	0.5	8.4
Phase III	5.6	540	35	23.2	14.5	1.6
Total	**46.1**	**1080**	**35**	**36.1**	**28.1**	**1.3**

[a] Profits = revenues – operating cost.

Table 13
Post-benchmarking: indicators variation.

Indicator	*Current*	*Improved*	*Δ%*	*Average*	*Best practice*
Current steam consumption (GJ/adt)	21.1	15.5	−26.6	18.5	12.2
Water consumption (m^3/adt)	110.1	73.1	−33.6	75	40
Net thermal deficit (GJ/adt)	8.1	2.5	−69.1	2.4	0
Effluents energy content (EC_E)	0.26	0.11	−57.7	–	–
Flue gases energy content (EC_{FG})	0.07	0	−100	–	–
Water heating	0.22	0.06	−72.3	–	–
Condensate recovery rate (%)	46	57	23.9	60	75

investments of the project. However, the cost of the incremental steam producing capacity required by the cogeneration plant (51 t/h of HP steam) must be taken into account in the economic evaluation of the project; it is of 7.0 M$. The cost of the 35 MW cogeneration unit is 11.9 M$. The low PBT (1.6 a) makes the implementation of this phase very attractive.

4.5.4. *Economics of the global strategy*

The overall implementation with a PBT of one year is economically attractive at the current price of energy (Table 12). Further increases in the price of biomass and of electrical power and, the probable implementation of carbon credits will reduce the PBT.

4.6. *Post-benchmarking*

The changes of the indicators used for benchmarking following the implementation of the strategy proposed are given in Table 13. The values for the best practice are also included. The implementation of all measures will save 46.1 MW (5.6 GJ/adt) of steam and, the mill will then consume 15.5 GJ/adt; this is less than the typical Canadian Kraft mill average of 18.5 GJ/adt. The net thermal deficit will decrease from 8.1 to 2.5 GJ/adt. The mill eliminates its reliance on fossil fuels for steam production. The water savings will be 1080 m^3/h (37.0 m^3/adt) and the mill water consumption should be 73.1 m^3/adt, just below the Canadian average of 75 m^3/adt.

The energy content of the effluents is reduced from 0.26 to 0.11 MJ/MJ because part of their energy content is recovered and because fewer effluents are produced. In addition, the energy available from flue gases is completely recovered by cold streams above the pinch point. There is a substantial reduction of steam for water heating due to water reutilization and internal heat recovery.

The exergy destroyed in the process is reduced by 32%. This is achieved by eliminating the use of PRV's, decreasing the steam pressure levels and reducing the steam consumption of the process. In addition, the implementation of turbines generates 35 MW of power.

The application of the methodology brings the process close to the best practices. However, to convert the improved process in a best practice mill, new equipments should be installed in the process. This issue has not been addressed in this work.

5. Conclusions

Improvements of the process obtained by the unified methodology produced substantially more steam savings than would have been by applying the individual techniques that it comprises as shown in Section 4.3.

The first two stages, base-case definition and benchmarking, set the foundation for all analyses and, in particular, the identification of the process inefficiencies in the steam and water systems. The computer simulation is an essential tool to study the process thermal balance variations. The indicators based on energy and exergy content help quantify the efficiencies of the current steam production system as well as the exergy losses caused by a deficient internal heat recovery and water reutilization.

The energy and water interactions are the core of the analysis. Intensified water reduction resulted in higher steam savings and lower surface area requirements than if only internal heat recovery had been considered. The elimination of non-isothermal mixing increases the heat recovery below the pinch point. The utilization of the exergy destroyed is an effective and straightforward tool to identify the most inefficient mixing operations.

The implementation of energy upgrading combined with conversion devices generates revenues from the sale of electricity and strengthens the economics of a retrofit program. The replacement of the low efficiency biomass boiler is an opportunity to increase the steam production capacity for power production.

The use of energy, water and exergy performance indicators gives a broader view of the process energy efficiency as all driving forces are analyzed in terms of quantity and quality, and mode of utilization. The exergy analysis is used as a diagnostic tool rather than as a means to increase the energy efficiency.

The improved process is a low water and energy consumer with efficient steam and hot water production systems. The decrease of the exergy destroyed and lost is reflected in the possible shutdown of the fossil fuel boiler and the production of power.

The application of mathematical optimization on the third stage would probably produce further potential improvements and will be the focus of future work.

The implementation of the strategy would produce an eco-friendly process that does not require fossil fuel for producing steam; its water and steam consumptions would be below the Canadian average and it would have the ability to generate large revenues from the production of green electricity from biomass.

Nomenclature

a	year
η_i	Carnot coefficient
η	boiler efficiency
CBM	Bare module cost, CBM_{steel}=3.18; CBM_{Ti}=11.2 ($)
CTM	contingency cost ($)
CGR	auxiliary facility cost ($)
$C_{p,i}$	heat capacity (kJ/kg°C)
CR	condensate recovery (%)
DSC	dissolved solids concentration (ppm)
E_{SP}	energy supplied to the process by fuels for steam production (MW)
EC_E	indicator energy content effluents (MJ/MJ)
EC_{FG}	indicator energy content flue gases (MJ/MJ)
EC_T	indicator for the total energy content of effluents and flue gases (MJ/MJ)
EC_{WTot}	indicator energy required to heat up water (MJ/MJ)
EC	energy conversion
EU	energy upgrading
$Ex_{Fuels\ comb}$	exergy obtained by the fuels combustion (MW)
Ex_{Proc}	exergy required by the process (MW)
Ex_{SP}	exergy supplied to the process by fuels for steam production (MW)
Ex_{WTot}	total exergy required to heat up water (MW)
$Ex_{dest,\Delta THX}$	exergy destroyed associated by the temperature difference between steam and process heat sink (MW)
$Ex_{dest,PRVs}$	exergy destroyed associated with the adiabatic expansion of HP steam for producing MP and LP (MW)
$Ex_{dest,HPprod}$	exergy destroyed associated with the temperature difference between combustion gases and the HP steam temperature (MW)
$Ex_{destroyed}$	total exergy destroyed (temperature differences between heat sources and sinks and adiabatic expansion of steam)
$Ex_{lost,eff+FG}$	exergy lost associate with the effluents and flue gases (MW)
ExC_E	indicator exergy content of effluents (MJ/MJ)
ExC_{FG}	indicator exergy content of flue gases (MJ/MJ)
ExC_T	indicator of the total exergy content of effluents and flue gases (MJ/MJ)
ExC_{EC}	indicator cogeneration potential (MJ/MJ)
Ex_{Water}	exergy used to heat up water (MW)
ExC_{WTot}	indicator exergy required to heat up water (MJ/MJ)
Ex_U	useful exergy supplied to the process (MW)
h_{out}	enthalpy of steam (kJ/kg)
h_{in}	enthalpy of boilers feed water (kJ/kg)
HP	high pressure steam (kPa)
HHV	high heating values of fuels (kJ/kg)
HE	heat exchanger
HEN	heat exchanger network
I	investment ($)
IHR	internal heat recovery
LP	low pressure steam (kPa)
m	mass flow (kg/s)
m^v	mass flow of steam (kg/s)
m^f	mass flow of fuels (kg/s)
MCR	minimum cooling requirement (MW)
MER	minimum energy requirements (MW)
MEP	minimum effluent production (MW)
MP	medium pressure steam (kPa)
MHR	minimum heating requirement (MW)
MWC	minimum water consumption (MW)
NIM	non-isothermal mixing
OC	operating costs ($)
PBT	pay back time (a)
PP	pinch point (°C)
PRV	pressure release valve
R	revenues ($)
S	savings ($)
T_{in}	inlet temperature (°C)
T_{target}	target temperature (°C)
T	temperature of heat sources or sinks (°C)
T_i	temperature of effluents, flue gases, water (°C)
$T_{E.treat}$	effluent treatment temperature (°C)
T_{SAC}	condensation temperature of sulfuric acid (°C)
T_o	ambient temperature (°C, K)
WR	water reutilization

Acknowledgements

This work was supported by a grant from the R&D Cooperative program of the National Science and Engineering Research Council of Canada. The industrial partners to this project and most specially the mill which supplied the data are gratefully thanked. Mateos-Espejel received financial support from the Mexican Council of Science and Technology as a Ph.D. candidate.

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