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DEVELOPMENT OF A STRATEGY FOR ENERGY EFFICIENCY IMPROVEMENT IN A KRAFT PROCESS BASED ON SYSTEMS INTERACTIONS ANALYSIS

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DEVELOPMENT OF A STRATEGY FOR ENERGY EFFICIENCY IMPROVEMENT IN A KRAFT PROCESS BASED ON SYSTEMS INTERACTIONS ANALYSIS

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To my parents, my sister and my goddaughter
Luciana

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RÉSUMÉ

L'objectif de ce projet de recherche est de développer, valider et appliquer une méthodologie unifiée qui considère les interactions des systèmes qui affectent la performance énergétique du procédé Kraft et permet d'en améliorer l'efficacité. Le développement d'une stratégie d'implantation des mesures d'économie d'énergie est le résultat final. L'usine qui fait l'objet de cette étude et située dans l'est du Canada et produit environ 700 adt/d de pâte kraft blanchie.

L'industrie des pâtes et papiers est une des principales industries canadiennes ainsi qu'un des plus gros consommateurs d'eau et de d'énergie du secteur industriel. La hausse des coûts énergétiques et les réglementations environnementales ont amené l'industrie à réorienter ses efforts pour développer des programmes de conservation d'eau et d'énergie. Ces deux éléments sont généralement analysés séparément, cependant ils sont fortement interdépendants. Par conséquent, une méthodologie qui considère l'eau, l'énergie ainsi que la production et l'utilisation d'utilitaires est nécessaire.

La méthodologie développée comprend quatre étapes successives. La première est la définition et la caractérisation du procédé, car la mise à disposition d'un modèle de simulation fiable et représentatif est essentielle à l'optimisation énergétique. Une procédure qui inclut quatre volets est proposée: la collecte de données, la construction du diagramme de procédé, l'analyse des systèmes utilitaires, et le développement de la simulation. Les systèmes d'eau et d'énergie sont les axes principaux de la simulation. La deuxième étape de la méthodologie est l'évaluation de l'efficacité énergétique actuelle. Le but est d'identifier les inefficacités du procédé et d'établir des directives pour le développent des mesures d'amélioration. L'efficacité du procédé est évaluée par comparaison avec la pratique industrielle et l'application de nouveaux indicateurs énergétiques et éxergétiques. Les besoins minimums d'énergie et d'eau du procédé sont aussi déterminés lors de cette étape. La troisième étape, qui comprend la définition des mesures d'économie d'énergie techniquement faisables, est le noyau de la méthodologie. Plusieurs techniques sont appliquées dans une procédure itérative pour mettre en évidence les synergies existantes. L'objectif est d'améliorer le procédé en maximisant les économies d'énergie et en minimisant l'investissement requis. La quatrième étape est l'implantation de la stratégie. Puisque

les configurations et les conditions opératoires varient d'un procédé à l'autre, il est important de développer une stratégie d'implantation des mesures d'économie, générale et avantageuse pour différents cas. Pour le cas de base considéré, une stratégie qui correspond au plan de gestion de l'usine est choisie, elle comprend trois phases: l'élimination du combustible fossile, la production de puissance et la libération de vapeur. Une analyse comparative subséquente est réalisée afin de quantifier l'amélioration de l'efficacité du procédé suite à l'implantation des mesures d'économie d'énergie. Les indicateurs de performance sont recalculés.

L'amélioration de l'efficacité du procédé grâce à l'application de la méthodologie unifiée permet d'économiser plus d'énergie par rapport aux techniques typiques appliquées individuellement. L'implantation des mesures proposées permet à l'usine d'économiser 5.6 GJ/adt (27% des besoins actuels) de vapeur, 32 m³/adt (34% des besoins actuels) d'eau, ainsi que de générer 44.5 MW d'électricité.

Le résultat de l'application de la méthodologie unifiée est un procédé vert qui n'utilise pas de combustible fossile, consomme moins d'eau et de vapeur que la moyenne canadienne, et produit de l'électricité à partir de la biomasse.

ABSTRACT

The objective of this thesis is to develop, validate, and apply a unified methodology for the energy efficiency improvement of a Kraft process that addresses globally the interactions of the various process systems that affect its energy performance. An implementation strategy is the final result. An operating Kraft pulping mill situated in Eastern Canada with a production of 700 adt/d of high-grade bleached pulp was the case study.

The Pulp and Paper industry is Canada's premier industry. It is characterized by large thermal energy and water consumption. Rising energy costs and more stringent environmental regulations have led the industry to refocus its efforts toward identifying ways to improve energy and water conservation. Energy and water aspects are usually analyzed independently, but in reality they are strongly interconnected. Therefore, there is a need for an integrated methodology, which considers energy and water aspects, as well as the optimal utilization and production of the utilities.

The methodology consists of four successive stages. The first stage is the base case definition. The development of a focused, reliable and representative model of an operating process is a prerequisite to the optimization and fine tuning of its energy performance. A four-pronged procedure has been developed: data gathering, master diagram, utilities systems analysis, and simulation. The computer simulation has been focused on the energy and water systems. The second stage corresponds to the benchmarking analysis. The benchmarking of the base case has the objectives of identifying the process inefficiencies and to establish guidelines for the development of effective enhancement measures. The studied process is evaluated by a comparison of its efficiency to the current practice of the industry and by the application of new energy and exergy content indicators. The minimum energy and water requirements of the process are also determined in this step. The third stage is the core of the methodology; it represents the formulation of technically feasible energy enhancing options. Several techniques are applied in an iterative procedure to cast light on their synergies and counter-actions. The objective is to develop a path for improving the process so as to maximize steam savings while minimizing the investment required. The fourth stage is the implementation strategy. As the

existing process configuration and operating conditions vary from process to process it is important to develop a strategy for the implementation of energy enhancement programs in the most advantageous way for each case. A three-phase strategy was selected for the specific case study in the context of its management strategic plan: the elimination of fossil fuel, the production of power and the liberation of steam capacity. A post-benchmarking analysis is done to quantify the improvement of the energy efficiency. The performance indicators are computed after all energy enhancing measures have been implemented.

The improvement of the process by applying the unified methodology results in substantially more steam savings than by applying individually the typical techniques that it comprises: energy savings of 5.6 GJ/adt (27% of the current requirement), water savings of 32 m³/adt (34% of the current requirement) and an electricity production potential of 44.5MW.

As a result of applying the unified methodology the process becomes eco-friendly as it does not require fossil fuel for producing steam; its water and steam consumptions are below the Canadian average and it produces large revenues from the production of green electricity.

CONDENSÉ EN FRANÇAIS

L'efficacité énergétique est d'une importance primordiale pour les industries chimiques énergétiquement intensives qui continuent d'utiliser des combustibles fossiles. La mondialisation des marchés a provoqué une course à la réduction des coûts de production, y compris ceux liés à l'énergie. La mise en œuvre de programmes de réduction d'énergie est essentielle pour que les industries manufacturières dans les pays industrialisés restent compétitives. Par conséquent, une grande variété de méthodologies et de technologies ont été développées. Ces méthodologies utilisent des techniques spécifiques qui sont destinées à améliorer une section du procédé mais qui ne considèrent pas les interactions existantes entre les systèmes utilitaires d'eau et de vapeur et les opérations unitaires. De plus, la façon dont le procédé est évalué n'est pas toujours complète et correcte. Pour cette raison, il est essentiel de proposer une méthodologie qui permettrait d'évaluer le procédé global et d'identifier des mesures d'économie d'énergie en considérant les interactions entre les systèmes utilitaires et le procédé.

L'industrie des pâtes et papiers est un des plus gros consommateurs d'énergie du secteur industriel au Canada, et représente 25% de la consommation d'énergie annuelle au niveau national. Bien que beaucoup d'efforts aient été déployés pour identifier les possibilités de réduire les coûts d'énergie en améliorant l'efficacité énergétique de ces usines, le potentiel de réduction reste encore important. Les usines canadiennes de pâte kraft comblent par elles mêmes environ 60% de leurs besoins en énergie mais peuvent encore augmenter ce pourcentage, la recherche et la mise en œuvre des technologies à haut rendement énergétique devraient permettre de concevoir et exploiter une usine entièrement autosuffisante

L'usine objet de cette étude produit environ 700 adt/d de pâte kraft blanchie. Les copeaux de bois sont d'abord soumis à une action chimique dans des lessiveurs où la lignine, l'agent liant les fibres de cellulose, est dégradée et solubilisée. La décharge des lessiveurs est ensuite évacuée dans des réservoirs de dépression. Un système de lavage sépare les fibres de la liqueur résiduaire de cuisson (liqueur noire) qui contient les sous-produits de la cuisson et les matières organiques dissoutes. La pâte lavée est blanchie au ClO₂, séchée, découpée en feuilles et vendue. La liqueur noire séparée de la pâte est d'abord concentrée par évaporation dans deux séries parallèles

d'évaporateurs à effets multiples et est ensuite envoyée à la chaudière de récupération où les matières organiques sont brûlées pour la production de vapeur, et où les produits chimiques oxydés sont réduits et récupérés sous forme d'un salin qui est recaustifié avec de la chaux vive. Les produits chimiques ainsi régénérés sont retournés aux lessiveurs. Dans le procédé Kraft une forte interaction entre les systèmes utilitaires d'eau et de vapeur existe.

Dans le cadre de ce travail, une méthodologie d'amélioration de l'efficacité énergétique d'un procédé chimique a été développée, ses objectifs principaux étant :

- La définition correcte et l'évaluation du cas de base et
- L'amélioration énergétique du procédé en combinant plusieurs techniques d'analyse, les interactions entre les systèmes utilitaires et le procédé, et les contraintes économiques et techniques.

La méthodologie comprend quatre étapes successives :

- La définition et la caractérisation du procédé;
- L'évaluation de son efficacité énergétique actuelle;
- L'analyse de toutes les interactions des systèmes du procédé;
- La stratégie d'implantation des mesures d'amélioration identifiées.

La première étape, souvent négligée, est le développement détaillé des systèmes utilitaires, du diagramme de procédé et des bilans d'eau et d'énergie. Le développement d'une simulation représentative du procédé global est fondamental pour une étude énergétique. La simulation est la source principale de données et un outil permettant d'évaluer l'impact des changements proposés sur la configuration du procédé.

Pour satisfaire les besoins en vapeur de l'usine considérée, deux chaudières de récupération, une chaudière à biomasse et une chaudière à mazout produisent de la vapeur à haute pression. Une partie de la vapeur à haute pression est directement utilisée et le reste est dépressurisé, dans des

vannes de détente, à deux niveaux inférieurs, la moyenne pression et la basse pression. Une turbine activée par de la vapeur à haute pression entraine les équipements de séchage et mise en feuille. Les chaudières de récupération produisent 65% de la demande moyenne annuelle de vapeur de l'usine, la chaudière à biomasse produit 25% et le restant (10%) est produit par la chaudière à mazout. La chaudière à biomasse consomme des déchets de bois provenant de scieries régionales. La consommation totale de vapeur de l'usine est de 21.1 GJ/adt. Une petite quantité de vapeur est exportée à une scierie avoisinante.

L'usine utilise de l'eau à cinq niveaux de température: froide (4°C en hiver, 20°C en été), tiède (44°C) et chaude (58, 62 et 71°C). L'eau tiède est générée dans les condenseurs de la section de concentration de la liqueur noire. L'eau chaude à 58°C est produite par échange indirect de chaleur avec les effluents de la section de concentration. Le reste de l'eau chaude est obtenue comme suit : la température de l'eau tiède est portée à 53°C par récupération interne de chaleur, et ensuite à 62°C par injection directe de vapeur. Une partie de l'eau à 62°C est utilisée, et le reste est chauffé à 71°C par échange indirect de chaleur avec de la vapeur. La consommation totale d'eau dans le procédé est de 110 m³/adt.

La seconde étape de la méthodologie comprend l'évaluation du procédé par comparaison de divers indicateurs avec la pratique industrielle. Toutefois, les résultats obtenus grâce à cette méthode ne fournissent pas suffisamment d'information sur les moyens d'améliorer le procédé. Par conséquent, une nouvelle procédure a été développée. Elle considère de nouveaux indicateurs basés sur le contenu énergétique et éxergétique des effluents et des gaz de fumée, l'éxergie requise par le procédé et fournie par le système utilitaire et, la réutilisation d'eau. Les analyses de pincement thermique et d'eau sont utilisées pour déterminer la quantité maximale et théorétique ment possible de récupération interne de chaleur et d'eau.

Le contenu énergétique des effluents et des gaz de fumée est un indicateur d'utilisation excessive de vapeur. Plus d'énergie est rejetée avec ces flux de chaleur, plus de vapeur est requise par le procédé. Par ailleurs, la production d'effluents est un indicateur d'utilisation excessive d'eau.

Tous les procédés chimiques respectent la loi de conservation d'énergie. Mais, cette loi ne tient pas compte de la dégradation d'énergie dans un procédé irréversible. L'éxergie est un indice de la

qualité et de la quantité d'énergie impliquée dans des transformations qui ont lieu dans le système et des échanges à travers ses frontières. Par conséquent, l'éxergie peut également être utilisée comme un indicateur de l'efficacité d'un procédé.

La consommation du vapeur de l'usine considérée est supérieure à la moyenne canadienne qui est de 18.5 GJ/adt. Le déficit thermique net soit la différence entre la vapeur produite par les chaudières de récupération et la vapeur consommée par le procédé est de 8.1 GJ/adt, une valeur bien au-dessus de la moyenne canadienne dont la valeur est 2.4 GJ/adt. La consommation totale d'eau est aussi supérieure à la moyenne qui est de 75 GJ/adt. Environ 60% de l'éxergie fournie par les combustibles est détruite ce qui indique un potentiel important de conversion d'énergie qui est actuellement perdu. L'optimisation des niveaux de pression de vapeur, l'amélioration de l'efficacité des chaudières et l'implantation de turbines peuvent égalent réduire la quantité d'éxergie détruite.

Dans le cas du procédé étudié, le besoin minimum de chauffage est de 123 MW, le besoin minimum de refroidissement est de 10 MW et le point de pincement est situé à 71°C. Un intervalle de température minimal entre les courbes composites de 10°C est utilisé. La quantité maximale de récupération interne de chaleur est de 192 MW. Le besoin minimum d'eau fraîche est de 1000 m³/h, la production minimale d'effluents est de 875 m³/h et le pincement est situé à 0 ppm de solides dissous. Le potentiel maximal de réutilisation d'eau est de 1360 m³/h.

La troisième étape de la méthodologie proposée comprend l'analyse des interactions entre les systèmes du procédé. Plusieurs outils destinés à améliorer l'efficacité énergétique d'un procédé chimique sont disponibles, la récupération interne de chaleur et la réutilisation d'eau sont parmi les plus utilisés. Toutefois, ces outils ne considèrent pas les fortes interactions qui existent entre l'eau et l'énergie. Pour cette raison, les résultats obtenus par une analyse peuvent limiter les options générées par l'autre. Pour maximiser les économies dans un contexte global, les deux analyses doivent être appliquées ensemble et de manière itérative. De plus, d'autres outils comme l'élimination de points de mélange non isothermiques, la récupération des condensats, et l'augmentation de température des effluents doivent être considérés.

L'amélioration de la récupération interne de chaleur nécessite l'implantation d'un réseau d'échangeurs de chaleur, dont la configuration dépend du degré de réutilisation d'eau et de la présence des points de mélanges non isothermiques. Les mesures de réutilisation d'eau économisent de l'eau et de la vapeur, quant à l'élimination des points de mélanges non isothermiques, elle peut se faire par modification de la configuration des mélanges ou pour récupération interne de chaleur. L'élimination des points de mélanges non isothermiques doit être faite après l'implantation des mesures de réutilisation d'eau. L'augmentation de la température des sources de chaleur est atteinte après la maximisation de la récupération interne de chaleur. Par contre, la conception du réseau d'échangeurs de chaleur peut être modifiée pour créer des opportunités d'intégration d'une pompe à chaleur. L'augmentation de la récupération des condensats doit être basée sur un procédé où toutes les économies de vapeur possibles par d'autres méthodes ont déjà été identifiées. L'implantation des technologies de conversion d'énergie, telles que les turbines doit être réalisée après que les économies de vapeur ont été maximisées tout en ciblant un potentiel d'augmentation de la production de puissance. Les indicateurs de contenu énergétique, la réduction de la demande en vapeur et la surface du réseau d'échangeurs de chaleur sont utilisés pour évaluer le degré des interactions possibles.

Étant donné que la configuration du procédé et les conditions opératoires varient d'une usine à l'autre, il est important de développer une stratégie d'implantation de programmes d'efficacité énergétique de façon qu'elle puisse servir à plusieurs usines. L'ordre optimal d'implantation peut être différent de l'ordre dans lequel les interactions des systèmes ont été analysées, car les facteurs économiques sont prédominants lors de la formulation de cette stratégie.

La stratégie proposée sera implantée de manière graduelle. La première phase comprend l'élimination de la production de vapeur par combustible fossile et les mesures correspondantes sont la récupération des condensats, la réutilisation des effluents et la récupération interne de chaleur. Cette phase s'avère très attrayante à cause du coût élevé des combustibles fossiles. L'objectif de la deuxième phase est de réduire d'avantage la consommation de vapeur pour augmenter le potentiel de génération de puissance. Les mesures proposées dans cette phase semblent moins attrayantes du point de vue économique parce que la réduction de la consommation de vapeur est calculée par rapport aux économies de vapeur à bas coût, générée à

partir de biomasse. Toutefois, elles sont essentielles pour augmenter les profits grâce à la vente d'électricité. La troisième phase consiste en l'implantation de pompes à chaleur à absorption et des turbines pour la cogéneration. Ces deux technologies peuvent être combinées de façon que la vapeur sortant de la turbine devienne la force motrice de la pompe à chaleur. Cet arrangement, connu comme tri-génération, est avantageux pour la production de puissance et pour la réduction simultanée de la consommation d'utilités de chauffage et de refroidissement.

L'implantation des mesures proposées permet à l'usine d'économiser 46.1 MW (5.6 GJ/adt) de vapeur, ce qui abaisse la consommation totale à 15.4 GJ/adt, bien au-dessous de la moyenne canadienne pour un usine de pâte Kraft (18.5GJ/adt). Le déficit net thermique diminue de 8.1GJ/adt à 2.5 GJ/adt, ce qui contribue à réduire la dépendance de l'usine vis-à-vis des combustibles achetés. L'économie d'eau est de 1080 m³/h (37.02 m³/adt) et sa consommation dans le procédé est de 73.1 m³/adt, légèrement au-dessous de la moyenne canadienne (75 m³/adt).

Le contenu énergétique des effluents rejetés est réduit de 0.26 à 0.11 (GJ effluents /GJ production de la vapeur) parce que leur énergie est récupéré et moins d'effluents sont générés; la quantité de vapeur destinée à chauffer l'eau est aussi réduite. Le contenu énergétique des gaz de fumées est entièrement récupéré par des courants froids situés au-dessus du point de pincement.

La destruction d'éxergie dans le procédé est réduite de 32% suite à l'optimisation des niveaux de pression de vapeur, l'élimination de vannes de détente et par la diminution de la consommation de vapeur. De plus, l'implantation des turbines permet de générer 44.4 MW de puissance.

L'amélioration du procédé grâce à l'application de la méthodologie unifiée permet d'économiser plus de vapeur que par l'application indépendante des techniques typiques.

Les deux premières étapes, la définition du cas de base et l'analyse comparative, bâtissent le fondement pour toutes les analyses subséquentes. Les indicateurs basés sur les contenus énergétique et éxergétique permettent d'analyser l'efficacité du système actuel de production de vapeur ainsi que les pertes d'éxergie dues à l'absence des mesures de récupération interne de chaleur et de réutilisation d'eau. Le fait que des facteurs, tels que l'énergie, l'eau et l'éxergie sont analysés, donne une vision plus large de l'efficacité énergétique car toutes les forces motrices

sont analysées en termes de quantité, qualité et mode d'utilisation. Le procédé amélioré, suite à l'application de la méthodologie proposée, devient un bas consommateur d'eau et d'énergie et il possède des systèmes efficaces de production de vapeur et d'eau chaude. La réduction d'éxergie détruite et perdue permet la fermeture de la chaudière à combustible fossile et l'augmentation de la production de puissance.

Le résultat final de la méthodologie unifiée est un procédé vert qui n'utilise pas de combustible fossile, consomme moins d'eau et de vapeur que la moyenne canadienne et produit de l'électricité à partir de biomasse (bio-énergie).

Grâce aux résultats obtenus dans le cadre de ce travail, de nouvelles perspectives de recherche s'ouvrent. En ce qui concerne l'évaluation de l'efficacité énergétique, il serait intéressant de mener des études plus approfondies sur l'analyse exégétique de toutes les opérations unitaires, quant à l'analyse des interactions, le développement d'une procédure d'optimisation mathématique pourrait résulter en une réduction plus importante de la consommation d'eau et de vapeur. L'application de la méthodologie devrait être considérée lors de la transformation d'une usine de pâte Kraft en une bioraffinerie verte et durable.

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NOMENCLATURE

Symbol	Description	Units
AHP	Absorption heat pumps	
ŋi,	Carnot coefficient	
C_{pi} ,	Heat capacity	kJ/kg*K
DSC	Dissolved solids concentration	ppm
E_{SP}	Energy supplied to the process (MW)	MW
EC_E	Indicator energy content effluents	MJ/MJ
EC_{FG}	Indicator energy content flue gases	MJ/MJ
	Indicator for the total energy content of effluents and	
EC_T	flue gases	MJ/MJ
$ECW_{Tot} \\$	Indicator energy required to heat up water	MJ/MJ
Ex_{Proc}	Exergy required by the process	MW
Ex_{SP}	Exergy supplied to the process by fuels	MW
Ex_{Water}	Total exergy required to heat up water	MW
$Ex_{\text{dest},\Delta THX}$	Exergy destroyed -steamutilization	MW
$Ex_{dest,PRV's}$	Exergy destroyed - adiabatic expansion HP	MW
$Ex_{\text{dest}, \text{HPprod}}$	Exergy destroyed - HP steam production	MW
$Ex_{lost,eff+FG}$	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
	Indicator of the total exergy content of effluents and flue	
ExC_T	gases	MJ/MJ
$ExC_{Cog} \\$	Indicator cogeneration potential	MJ/MJ
$ExCW_{Tot} \\$	Indicator exergy required to heat up water	MJ/MJ
HEN	Heat exchanger network	
HP	High pressure steam	kPa
LP	Low pressure steam	kPa
M	Mass flow	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	
PP	Pinch point	$^{\circ}\mathrm{C}$
PRV	Pressure release valve	
T_{in}	Inlet temperature	$^{\circ}\mathrm{C}$
T_{target}	Target temperature	°C
T	Temperature of heat sources or sinks	°C
T_{ET}	Effluent treatment temperature	°C
T_{SAC}	Condensation temperature of sulfuric acid	$^{\circ}\mathrm{C}$
T_{o}	Ambient temperature	°C
T_{lm}	Mean logarithmic temperature	°C
VRHP	Vapour recompression heat pump	

CHAPTER 1 INTRODUCTION

1.1 Problem

The enhancement of the energy efficiency 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 modifying the quality of the end product. The implementation of energy reduction programs is essential for all manufacturing industries in industrially mature countries to remain competitive. In response, a wide variety of methodologies and technologies have emerged to improve the chemical processes. These methodologies tend to focus on a specific enhancing technique and also on a specific process section without regard to the interactions between the utility systems, water and steam, and the unit operations. The application of individual techniques will indeed lead to reduction 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 utility systems, the process diagram 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, 2000a). The simulation is the principal source of data and also an instrument to asses the impacts of possible process modifications. The evaluation of the process sections or units is achieved by benchmarking (Francis et al., 2006; Towers and Turner, 1998). 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 insulation, 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.

The interactions between the utilities systems and the process must be identified to formulate technically feasible energy enhancing options. There are various techniques to improve the energy efficiency of a process; however, these techniques must be applied in an iterative procedure to cast light on their synergies and counter-actions. The two best known techniques and most often utilized are internal heat recovery and water reutilization by the application of systems closure measures. In response, milestone methodologies such as Pinch analysis[®], Water Pinch and Exergy Analysis have been developed.

The objective of Pinch analysis[®] is to increase process to process heat exchanges by the design of a retrofit heat exchanger network (HEN). It can be applied to complex industrial sites such as petroleum refineries. It can incorporate complementary techniques such as energy conversion and upgrading.

Water Pinch (Dhole, 1998; El-Halwagi and Manousiouthakis, 1989; Wang and Smith, 1994) is an extension of Pinch Analysis[®] but with a water reutilization perspective. The 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. 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 et al., 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. The reduction of exergy

lost associated to internal heat recovery was the objective of this study. 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., 1998b) in the computation of the exergetic efficiency. Marechal and Favrat (2005) demonstrated the combined used of exergy analysis and process integration techniques to analyse 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 fields of action for each methodology. Exergy analysis identifies the operations with poor performance and Pinch Analysis[®] the heat transfer inefficiencies or lack of internal heat recovery.

The interactions between energy and water have also been studied. Savulescu et al (2005a) proposed a method to reduce water and steam consumption in water networks by the utilization of a diagram that incorporates the temperature and contaminants concentration to develop measures for internal heat recovery and water reutilization. Schaareman *et al.* (2000) applied Pinch Analysis and Water Pinch in sequence but without analyzing the impacts of water reutilization strategies in the thermal side of the process. Savulescu and Alva-Argaez (2008a) proposed a methodology for the elimination non isothermal mixing used for direct heat recovery, to reduce the steam demand in water and steam systems. Lafourcade et al (2006) developed a methodology where two types of water reduction projects are proposed: projects formulated by benchmarking the current reutilization strategies, and based on an analysis of the thermal composite curves so as to consider thermal constraints.

There are other energy enhancing techniques, such as: the increment of the rate of condensate return to the utility system, the elimination of non isothermal mixing for heating or cooling and the adjustment of the temperature or pressure levels of the utilities. These techniques are often ignored in energy retrofit projects yet, they can have a significant effect on the overall steam consumption but they may also limit the scope of internal heat recovery and system closure. There are also vast amounts of heat at low potential in various process streams near ambient temperature, which cannot practically be recovered by the techniques mentioned above. Upgrading some of this heat to a useful level by means of a heat pump can, in some cases, yield

significant energy gains. Absorption heat pumps can be attractive because of their specific characteristics (Bakhtiari et al 2009). Finally the availability of excess steam production capacity generated by an energy integration project can be used to produce electric power for sale thus generating revenues to offset energy costs and investments.

Therefore, there is a need for a methodology that analyzes the energy efficiency of the processes globally, which integrates several energy enhancing techniques, and that take into account the systems interactions. The final result should be a strategy where different kinds of measures are implemented conjointly with the objective of improving the overall energy efficiency.

1.2 General objective

The objective of this thesis is to develop, validate, and apply a unified methodology for energy efficiency improvement that addresses globally the systems interactions in a Kraft process.

1.3 Structure and organisation

In Chapter II, the context of the thesis is explained. The specifics of the Kraft process are introduced as well as the current situation of the Canadian pulp and paper (P&P) industry.

In Chapter III, the literature review of the techniques used for improving energy efficiency is presented. Several studies concerning the internal heat recovery, water reutilization, energy-water studies and, energy upgrading and conversion are introduced. The application of these techniques to P&P processes is also discussed. The conclusion of this chapter states the specific objectives of this thesis. The four stages of the overall methodology are described as well as their purpose.

In Chapter IV, the definition and characterization of the base case is performed. The details of the development of the steam and water systems, the required data to construct them and the computer simulation are presented.

In Chapter V, the benchmarking analysis is performed. A new benchmarking procedure has been developed to evaluate the current energy efficiency of the process. The 5 phases of the procedure

are explained: data compilation, comparison to the industrial practices, utilization of new energy and exergy content indicators, targeting by Pinch Analysis and Water Pinch, and a synthesis.

In Chapter VI, the systems interactions analysis is performed. A method is presented to identify and evaluate the systems interactions in the base case. Several energy enhancing techniques are considered: internal heat recovery, water reutilization, elimination of non isothermal mixing, energy upgrading & conversion, and condensate recovery.

In Chapter VII, a strategy for implementing the measures that is the result of the systems interactions analysis is presented. The strategy has 3 objectives: elimination of fossil fuel, liberation of steam capacity and production of power. Economical and technical constraints are considered. A post-benchmarking analysis is also performed.

In Chapter VIII, the unified methodology developed in this thesis is presented. It consists of four phases: definition and characterization of the base case, benchmarking, systems interactions analysis, and implementation strategy.

In the general discussion, the highlights of each step of the methodology are presented.

In the conclusions and recommendation, the originality and topics for future research are discussed.

In the appendix the overall steam and water systems are presented. A list of publications which have been developed is attached.

CHAPTER 2

CONTEXT OF THE STUDY

The object of this study is an operating Kraft pulping process situated in Eastern Canada. The pulp and paper (P&P) industry has been a major contributor to the North American economy for many years. Due to the simultaneous impact of several factors such as the intense world wide competition from mills producing fiber from fast-growing forests, the reduced demand for newsprint and pulp, and the high cost of energy, the industry has been under heavy pressure, and unable to generate enough profit.

The total production of paper products in Canada is of 30 345 000 tonnes, which represents a declined of 5% in the period 2000-2005 as published by PPPC (2005). In the same period the sales of the industry have decreased by 25%.

P&P processes are 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, its consumption of fossil fuel remains a heavy burden. Its high water consumption compounds its energy challenge (Turner, 1994). Overall, energy accounts for up to 30% of the total pulp manufacturing cost in Canada. Facing increasing energy costs and more stringent environmental regulations, the industry has refocused its research efforts towards energy efficient practices and technologies and water conservation programs.

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 the water, to concentrate the black liquor and for pulp drying.

Systematic energy optimization with the application of advanced methodologies is necessary to improve the energy efficiency of P&P processes in a cost effective way.

2.1 Kraft process

The Kraft process is the dominating pulping process by which wood chips are transformed into paper pulp, the intermediate material from which a very broad spectrum of finished or semifinished paper products are made. Its simplified representation is given in Figure 2-1. A typical Kraft pulp mill uses biomass (wood chips), fuel (fossil and hog), chemicals, and water to produce market pulp, steam and power. The major components of wood are cellulose (40-47%), hemicellulose (25-35%), lignin (16-31%), and extractives (2-8%) (Smook, 2002). The core of the Kraft process is the chemical delignification step in which the individual cellulosic fibers are separated from lignin to form pulp. The Kraft delignification agent (white liquor) is a mixture of sodium hydroxide (NaOH) and sodium sulfide (Na₂S). For bleachable grade pulp, 45-65% of the wood mass is dissolved in the pulping liquor during delignification. The dissolved material consists primarily of degraded hemicellulose, cellulose, lignin and various others organics (the extractives). After delignification, the fibers are washed, and chemically bleached. Finally, they are drained, pressed, and thermally dried in a pulp machine. An important characteristic of the Kraft process is that the spent delignification liquor (black liquor), separated from the fibers in the washing step, is concentrated and burnt to produce steam and an inorganic smelt. The smelt composed of sodium carbonate (Na₂CO₃) and sodium sulfide is dissolved to form green liquor, which is reacted with quick lime (CaO) to regenerate the original white liquor.

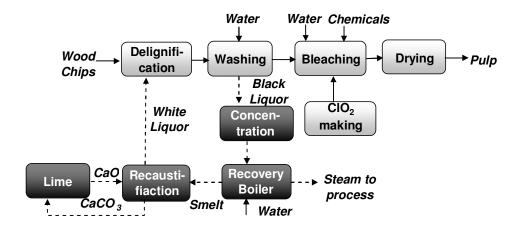


Figure 2-1. Simplified diagram of the Kraft process

2.1.1 Delignification

In the Kraft process the delignification occurs in a chemical reactor named the digester. The objective is to remove as much lignin as possible without losing large quantities of cellulose and hemicelluloses. For this purpose a chemical mixture of caustic soda and sodium sulphide (100 – 110 g/L), named white liquor, is employed. Before bleaching, about 90% of the lignin has been dissolved. The unbleached pulp contains 36% cellulose, 8% hemicellulose and 2 % lignin, based on the original weight of wood (Van Lierop, 2006).

Depending on the type of digester (continuous or batch), the live steam requirement varies; for a continuous digester it is 1.7 GJ/adt (Francis et al., 2004) and 4.78 GJ/adt for a batch digester (Francis et al., 2006).

2.1.2 Washing

A series of counter-current washers are used to separate the black liquor from the fibres. An excess of water utilization, to increase washing efficiency, increases the steam demand in the black liquor concentration. On the other hand, ineffective washing results in high consumption of bleaching chemicals.

2.1.3 Bleaching

Chemical pulp bleaching removes the lignin that remains in the fibers after the chemical delignification. The primary objective is to produce pulp with high brightness. The secondary objectives are retaining brightness stability, high pulp cleanliness, and high cellulose content.

The steam consumption of a modern bleaching department using only 4 stages is about 2.3 GJ/adt (Francis et al., 2004). This section is also the highest water consumer of the process. The consumption depends on the age of the mill, the number of stages, and the degree of water reutilization. A conventional bleach plant uses between 25 to 60 m³/a.d.t and if the consumption is 100 m³/a.d.t, it would be considered excessively high (Turner, 1994).

2.1.4 Recovery loop

Most of the steam required by the process and the delignification chemicals are generated in the recovery loop of a Kraft process (Figure 2-2).

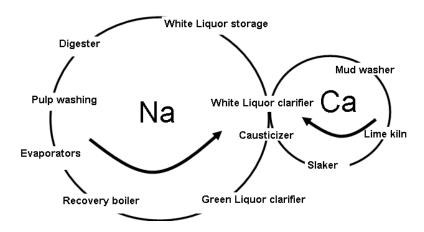


Figure 2-2 Utilization and recovery of Na and Ca in Kraft process

The recovery loop has three sections: the evaporators where the black liquor is concentrated; the recovery boilers where the concentrated black liquor is burnt to produce steam and recover an inorganic smelt, green liquor; this smelt is recaustified so as to regenerate the white liquor used in the delignification.

Evaporators. The so-called strong black liquor is concentrated to a 70 % dissolved solids content. The average steam consumption for a modern seven effect train of evaporators with one concentrator is calculated to be: 3.1 GJ/adt (Francis et al., 2004). Most of the warm water used in the process (40°C) is produced in this section.

Recovery boilers. The boilers burn the concentrated black liquor to produce steam and the inorganic smelt that will be recaustified.

Recaustification. The objective is to produce enough white liquor for the delignification at a minimum cost. The white liquor is produced by the soda-lime process represented by the following pathways.

Caustification reaction:

$$CaO + H_2O \longrightarrow Ca(OH)_2 + Na_2CO_3 \longrightarrow CaCO_3 + 2NaOH$$

Lime burning reactions:

$$CaCO_3 + heat \longrightarrow CaO + CO_2$$

2.1.5 Drying

This is the final stage of the process, it has two principal objectives: extraction of the water and formation of the fibre net. The dryers are, with the evaporators, the biggest energy consumers of the Kraft process. For a new mill the steam consumption is 2.3 GJ/adt (Francis et al., 2004). The average consumption of dryers in Canadian mill is 4.54 GJ/adt (Francis et al., 2006).

CHAPTER 3

LITERATURE REVIEW

On the basis of the general objective of this thesis, the literature review is divided in five parts; internal heat recovery, water reutilization, energy and water, exergy analysis and, energy conversion and upgrading. The conclusions of this chapter are the specific objectives of the thesis.

3.1 Internal heat recovery

Pinch Analysis is the standard tool to increase internal heat recovery. It was developed at the beginning of the 80's (Linnhoff et al., 1994a; Linnhoff et al., 1994b) and has been proven to achieve energy reductions between 25 to 35% (Linnhoff, 1994b). It is a structured approach used to maximize internal heat recovery within a process and to minimize its need for hot and cold energy supplied by utilities. It is well known that in order to ensure real net energy savings Pinch Analysis must be applied to a whole process or even to a complete site.

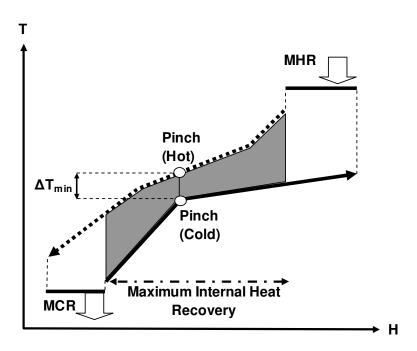


Figure 3-1 Example of the hot and cold composite curves of a process

The basis of Pinch Analysis is the display in a temperature vs enthalpy diagram of all possible heat transfers within the process (Figure 3-1). It consists of the hot and cold composite curves which respectively represent the heat availability and demand in the process and define the minimum energy requirement (MER) and the pinch point.

3.1.1 Applications of Pinch Analysis

The main objectives of applying Pinch Analysis have been to reduce the fossil fuel consumption, the atmospheric emissions and to set the basis for a continuous optimization (Linnhoff, 1994a). The resulting measures vary from individual projects to the total site integration. It has been widely applied in the petrochemical industry, as well as in the pulp and paper industry (Algehed, 2002; Algehed et al., 2000; Axelsson and Berntsson, 2005; Eastwood, 1988; Kemp, 2005; Rouzinou et al., 2003; Towers, 2003).

In pulp and paper processes the heat recovery loops of old mills were installed without considering the pinch point. Therefore economically attractive energy savings can be found just by respecting the principles of Pinch Analysis (Towers, 2003). The analysis has also been applied as a decision tool when looking to solve specific problems. For instance, the reduction of the effluent temperatures to improve the efficiency of their treatment (Noel and Boisvert, 1998) or the installation of new equipment (Berglin and Berntsson, 1998; Rouzinou et al., 2003).

The retrofit of the overall heat exchanger network has also been proposed for an operating Kraft process (Lutz, 2008) and for a model mill (Axelsson et al., 2006).

The grand composite curve (GCC), which is a diagram representing the net heat flows in the process, has been used to identify the excess utilization of hot utility or the availability of the heat contained in hot effluents (Axelsson and Berntsson, 2005). The combination of the GCC with optimization algorithms has been applied to define the optimum heat exchange network and to choose the best utility technology so as to develop an optimal utility system (Marechal and Kalitventzeff, 1998b). The adjustment of the steam pressure levels is also one of the GCC main applications (Marechal and Kalitventzeff, 1997). The GCC for the process and for the corresponding utility systems have also been compared so as to find opportunities for cogeneration (Dhole and Linnhoff, 1993; Marechal and Kalitventzeff, 1996b; 1998a).

The analysis of the process needs by means of the composite curves is, typically, the initial step of the energy studies. However, Rutkowski and Karp (2001) proposed an analysis of the utilities systems prior to the application of Pinch Analysis. Therefore, aspects such as the fuel utilization in the boilers, localization of all steam consumers, and the condensate return rate are the initial targets of the energy programs. The aim is to increase the economic attractiveness of the projects.

Pinch Analysis is mostly applied in retrofit situations. The chemical processes that were installed 30 years ago are not optimally integrated. However, the complete redesign of the corresponding utility systems or HEN would not be profitable. This is the case in the P&P industry. Therefore, in retrofit situations the capital cost trade-offs vs operating costs have always to be considered when applying Pinch Analysis (Linnhoff and Witherell, 1986).

In a typical retrofit situation the Pinch Analysis should also take into account constraints such as the physical distance between the streams, material, type of heat exchangers, auxiliary equipment, space requirements, maintenance cost and fouling (Carlsson et al., 1993). New curves have been proposed for retrofit projects so as to obtain information which is not given by the typical GCC (Nordman and Berntsson, 2001). There are four curves defined above the pinch point (Figure 3-2): one for the utility streams used in heaters (HUC), one for the process streams associated with the heaters (AHLC), other assuming that all needs will be satisfied by the highest temperature utility (EHLC), and another which represents the minimum ΔT to which a heat exchange can take place (THLC). The same curves are defined below the pinch point. The main objective of these curves is to graphically identify options for retrofit HEN while including technical factors. However, these aspects are taken into account in the design of the HEN, and optimization algorithms (MILP, MINLP) are usually employed for this purpose. These curves have been applied in the P&P industry to integrate usable excess heat in mills with low water consumption. The temperature of the associated hot streams must be high, typically above 80°C but still below the pinch point (Wising, 2003), such as the pre-evaporation of effluents (Bengtsson et al., 2002b). A combination with an optimization algorithm (based in MILP) has also been done to include all the economic, technical and practical constraints that the pinch analysis does not tackle (Bengtsson et al., 2002a).

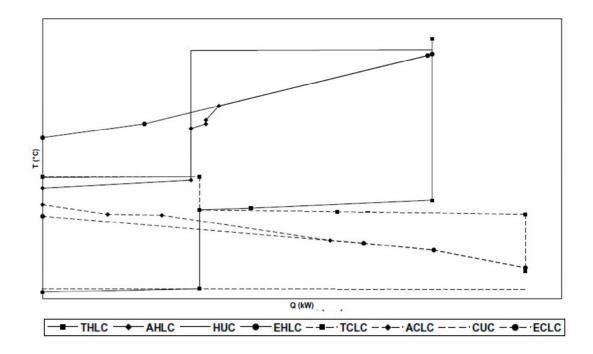


Figure 3-2 Advanced composite curves (Nordman and Berntsson, 2009)

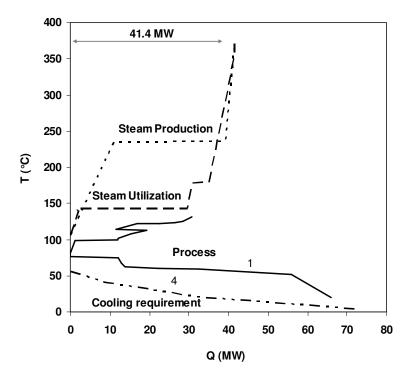


Figure 3-3 Combined process and utilities analysis by Mateos-Espejel et al (2007).

A similar approach has been proposed by Brown *et al* (2005), Mateos-Espejel *et al* (2007) and Perin-Levasseur *et al* (2008). The GCC for the process and the utility systems are constructed and

evaluated Figure 3-3. The objective is to analyze the utilization and production of the steam, and the actual requirements of the process. The measures proposed concern the better utilization of the utilities so as to increase the potential for combined heat and power production. This analysis should be performed before retrofitting the HEN.

In P&P processes with a significant degree of system closure there is an excess of heat illustrated by a surplus production of hot and warm water that has to be cooled and sent to the sewer. An analysis of the GCC can identify options to recover this heat by means of upgrading devices such as absorption heat pumps (Marinova et al., 2007). New evaporator designs have also been proposed to use the excess heat (Algehed, 2002). Another alternative to find a heat surplus in a mill is by means of pinch violations. The HEN gives solutions to eliminate all the inefficiencies, but some of them may not be economically feasible, so there will still remain excess heat that could be used for other purposes, like in the evaporators (Bengtsson, 2004). Antoher methodology has been developed to analyze the process from the perspective of the production and utilization of the utilities, combined with optimization models (Perin-Levasseur et al., 2006).

Drying operations have received particular attention due to their high energy consumption. The improvement depends on many technical situations such as heat losses, inlet moisture, and appropriate design. However in order to introduce heat recovery measures between the dryers and other processes, Pinch Analysis is needed. It has been shown that the heat recovery is limited by thermodynamic and economic factors (Kemp, 2005). In this case, the pinch analysis can be performed by section, so as to compare the pinch point. Heat might be exchanged with a nearby process whose pinch point is substantially above the dryer pinch temperature (≈100°C). Generally, the exhaust heat is recovered with the intention of pre-heating the inlet air at pulp and paper mills. Another study (Eastwood, 1988) shows that steam savings can be achieved by increasing the dew point of the exhaust gases. The problem with these works is that they do not consider the rest of the mill, restricting the analysis of their integration in the process.

There have been proposals for new dryer designs (Wising et al., 2002b), which try to increase their energy efficiency and heat integration. However, these options only can be applied in new processes, due to the high investment that would be required to change a dryer.

As mentioned previously, the temperature increase of effluents and the excess heat produced by system closure has been extensively studied. The impact of reducing the steam consumption and the amount of effluents produced also have also been investigated (Towers, 2004; Wising et al., 2002a). However, all previous analyses are based on the consequences of the mill closure.

The real case examples involve many streams in the design of the HEN, making its graphical solution difficult. Therefore, to solve these kind of problems, mathematical algorithms, such as mixed integer linear programming (MILP) have been applied to obtain optimal HEN designs (Papaoulias and Grossmann, 1983; Papoulias and Grossmann, 1983). The objective function is the minimization of cost or maximization of profit, and the constraints consider the pinch rules, the physical distance between the streams, or interdiction of some matches.

The Pinch Analysis is the standard tool for studying internal heat recovery aspects in a process. Nevertheless, it does not consider the efficiency of the equipment, the direct relation between energy and water reduction, and the relation between the utilization and production of the utilities.

3.2 Water reutlization

In transport phenomena the analogies between mass and heat transfer were the basis for developing the equations of mass transfer. The same concept was applied in pinch analysis to obtain a method for analyzing mass exchanges within a process (Shafiei et al., 2003). The exchange driving forces, differences in concentration and in temperature, and the quantities exchanged, mass and enthalpy are analogous. Therefore a diagram with the concentration and the mass exchange load to analyse water reutilization scenarios is similar to the one of temperature and enthalpy used for internal heat recovery.

The same similarity is found in the equipment used for the transfer. For the mass exchange operations, the equipment used are mass exchangers, defined as any direct-contact mass-transfer unit that employs a lean phase (solvents, adsorbents, ion-exchange resins or stripping agents) to selectively remove certain components (pollutants) from a rich phase (El-Halwagi, 1997). The lean phase must be immiscible in the rich phase and when the two phases are in contact, the

solutes from the rich phase transfer to the lean phase. The mass exchangers include the following unit operations: absorption, adsorption, ion exchange, leaching and stripping and extraction.

Three graphic techniques have been developed:

• Pinch diagram: El-Halwagi and Manousiouthakis (1989) developed the pinch diagram where the entity exchanged is a single or a group of chemical species (Figure 3-4); undesirable contaminants or products to be removed from the main process steam. The principle of the method consists of constructing composite diagrams of the rich and poor streams to determine the minimum quantities of mass separating agents.

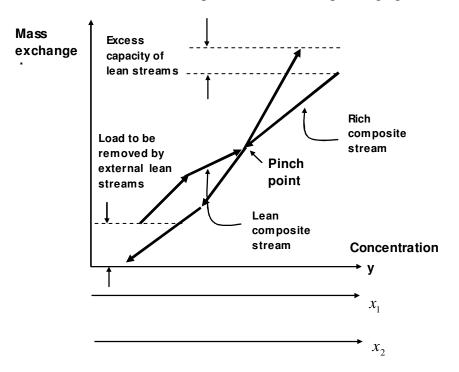


Figure 3-4 Pinch diagram

• Diagram for washing systems: Wand and Smith (1994) developed a diagram for the application of water pinch concepts to washing systems. Water is always in contact with other compounds and thus becomes contaminated. The water initially has zero contamination, but it increases with the mass transfer. If the water flow is decreased in specific equipment the contamination at the outlet increases, since the mass transfer remains the same (Figure 3-5). The reduction of water will be limited by a minimum flow

rate needed by the equipment; otherwise the outlet contaminant concentration reaches a maximum value.

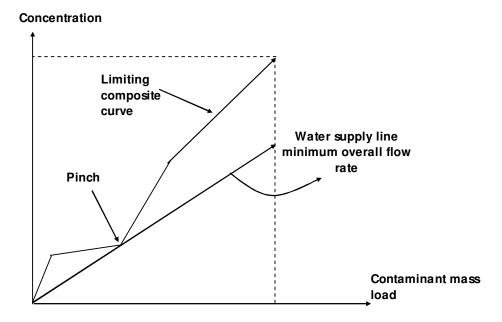


Figure 3-5 Composite concentration curve

- Water pinch diagram: Dhole (1998) developed a methodology of which a diagram that contains all the inputs and outputs in terms of purity and flow rate of the fluid is the main feature (Figure 3-6). Therefore, it is possible to find direct possibilities for reutilization or regeneration of fluid. This methodology tries to solve all the drawbacks of the previous approaches:
 - The transport phenomena problem where there are reactions, blowdowns, or several water-based streams entering and leaving a process unit
 - The limiting water profile is impractical when there is a minimum water flow rate for effective operation
 - Water flow rate is implicit in the mass exchange load
 - ➤ Multiple water concentrations cannot be visualized
 - Water network changes cannot be applied directly

This method can be applied to single phase processes, generally water based, where the main streams content of the desired product are enriched by reducing the level of contamination through a succession of operations, such as dilution, displacement or thickening (Shafiei et al., 2003). This is the case of the Kraft process.

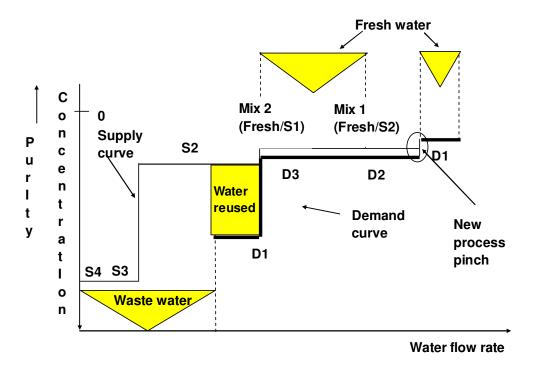


Figure 3-6 Fluid efficiency pinch diagram

3.2.1 Application of Water Pinch

The method proposed by Dhole (1998) has been used in the P&P industry to improve specific process sections, such as the paper machine (Jacob et al., 2002; Tripathi, 1996), the deinking plant (Koufos and Retsina, 2001), or the complete process (Jacob et al., 2002).

Lovelady and El-Halwagi (2007) applied the pinch diagram concept in combination with a mathematical model to track water and primary non process elements throughout the pulping process.

Optimization algorithms have been used to deal with the problems that the graphical methods cannot solve. The common objective of all algorithms is to minimize water consumption through

an optimized mass exchanger network. The applicability of the algorithms depends on the assumptions made.

Bagajewicz (2000) performed a review of the principal mathematic algorithms applied to the system closure in refineries.

- Nonlinear programming. They are formulated assuming a linearized model for a single component, and considering the necessity to remove all the contaminant loads; the constraints are the maximum inlet and outlet concentrations (Savelski and Bagajewicz, 2000). In the P&P industry this type of solution has also been applied (Brown et al., 2004) to minimize the costs of fresh water and, the connection and installation of the piping network. Two contaminants were considered, the total dissolved solids content and the calcium concentration.
- Mixed integer linear programming. They have been used to find the optimal network including several objective functions, such as the minimization of the number of interconnections, and the forbidden matches (Savelski and Bagajewicz, 2000).
- For solving multi-component systems. Doyle et al (1997) proposed an iterative method considering the linearization of the mass balance, and assuming that all the contaminants are at their maximum concentration. This approach can be used to simplify an otherwise nonlinear programming problem.
- Genetic algorithms. This method works similarly to the natural selection of the evolution of
 the species. It can involve different objective functions at the same time to get an optimal
 solution. Shafiei et al (2004) performed a combination with linear programming to achieve
 system closure in a P&P process.

3.3 Energy and water

Energy and water aspects are usually analyzed independently but in reality they are strongly interconnected. Water reutilization measures reduce fresh water consumption and effluent production; however, the average temperature in the process also increases (Syberg and Barynin,

1998). The utilization of the excess heat of process with low water utilization has been investigated so as to reduce the steam consumption by the implementation of external energy upgrading devices (Wising et al., 2005).

The combination of thermal and a water pinch analysis has been applied to a complete mill by Schaareman *et al* (2000). Both analyses were run in sequence and iteratively, the thermal pinch after the water pinch. However, thermal aspects were not taken into account to propose water reduction measures. Koufos and Retsina (2001) applied both approaches independently without analyzing the modification to the thermal balance.

A problem of water pinch analysis is the need of concentration data for different compounds in a process stream. Generally, the data gathered in P&P processes only includes the fibers (consistency). Savulescu *et al* (2005c) took into account that restriction, and analyzed the water system based on experience so as to identify inefficient configurations in a mill. As a result, internal heat recovery measures were not affected by the posterior implementation of water reutilization projects. A computer process simulation can give an approximation of the contaminant concentration, making possible the application of water pinch.

A combined water and energy analysis has been proposed by Savulescu *et al* (2005a). The general formulation requires a set of water using operations, identification of available water sources and the process constraints. The data required are flow rates, temperatures and contaminant concentration levels for inlet and outlet.

The analysis is based on a diagram that includes axis for the temperature, concentration and water flows. The objective is to obtain an optimum water network taking into account energy and contaminants restrictions (Figure 3-7). The operations are drawn as horizontal lines as long as the unit operations are isothermal.

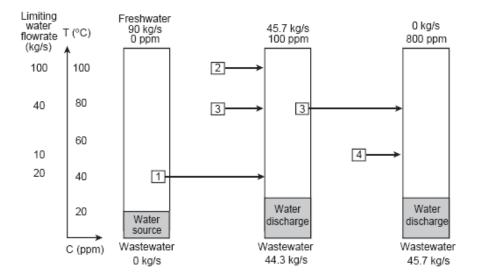


Figure 3-7 Grid diagram with temperature and concentration flow rates (Savulescu et al., 2005b)

In order to create the network, the operations are connected by water mains and (Figure 3-8). The vertical lines inside the water mains represent the water distribution and temperature targets.

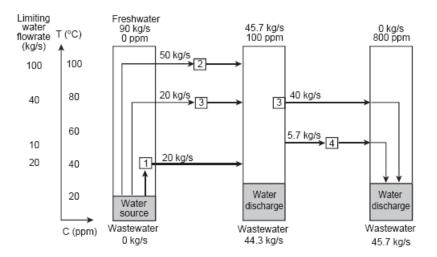


Figure 3-8 Water mains and identification of hot and cold streams (Savulescu, L. et al. 2005)

Operation 3 (Figure 3-9) has been subdivided in two parts by the 100 ppm water main. This results in a different water flow rate requirement on each side. Therefore, a uniform flow rate across the operation has to be reached. Thus, the point where operation 3 is fed is changed with the re-used stream. The water from the middle water main is supplied to the inlet of operation 3, which allows the same flow rate for operation 3 without violating the inlet contamination level.

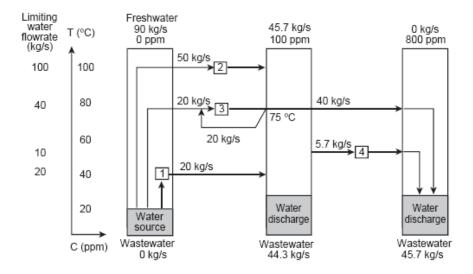


Figure 3-9 Merge operations (Savulescu, L. et al. 2005)

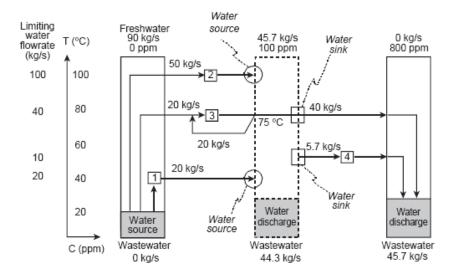


Figure 3-10 Identification of sources and sinks (Savulescu, L. et al. 2005)

The removal of the intermediate main at 100 ppm requires the connections between the sources and sinks at this level of concentration. The intermediate water main (100 ppm) has two sources and two sinks (Figure 3-10).

To achieve the combined energy and water minimization (eliminating intermediate main), three rules have been defined, taking into account streams mixing and splitting:

1) Distribution of the water reused from the hottest source

- 2) Connection of the water source with the nearest sink (temperature)
- 3) Introduction of nonisothermal mixing points if the temperatures of the sink operations are intermediate to the temperature of source operations.

The problem with this methodology is that it has only been applied in the water network, without considering the interactions with the rest of the process and the overall pinch point. As for all graphic-based analysis, a mathematic algorithm must be defined to solve a larger problem. Leewongtanawit and Kim (2008) developed an optimization algorithm to consider multiple contaminants, in water networks, based on the methodology proposed by Savulescu et al (2005b).

Nordman and Bertsson (2006) proposed new tank curves (Figure 3-11) associated with the different temperature levels in the water networks. The objective is to use the heat properly, so as to liberate the high temperature energy sources for energy upgrading. New temperature levels are proposed as a result.

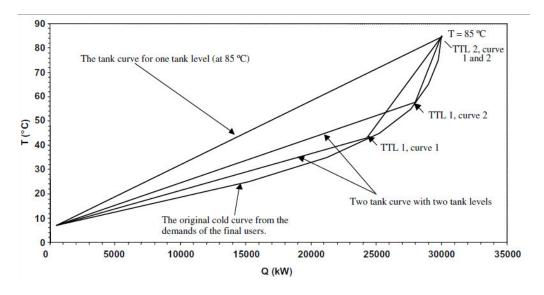


Figure 3-11 Tanks curves (Nordman and Berntsson, 2006)

A methodology, applied to a P&P process, for minimizing the energy and water use has been proposed by Lafourcade *et al* (2006). The methodology first involves a qualitative analysis, where a mill profile is obtained by benchmarking, water and energy audits, data collection, and the mill situation (previous studies and projects, and the strategic orientation). Based on this information, the short and long term objectives are set. The water and energy analysis involved the next steps:

- 1) Simulation of the process: A standard simulation of the process was done in order to verify the feasibility of the options proposed.
- 2) Process study: This step is based on benchmarking water and energy use, the identification of projects for water reutilization (like the vacuum sealing pumps) that the pinch analysis cannot identify, and typical ways to apply system closure in pulp mills. The proposition of new technologies (i.e. paper drying) is also done.
- 3) Modified pinch analysis: It refers to the identification of the process stream mixing points (direct heat exchange). A classical pinch analysis is done first with the definition of the HEN, and then some of the indirect exchangers are replaced by direct heat exchangers (mixture of contaminated and clean water). New composite curves are constructed taking into account the direct heat exchangers to identify new possible mixing points (Lafourcade et al., 2003). This is an iterative method for achieving water recirculation (mixture of clean and contaminated water) with an energy optimization objective.
- 4) Classical pinch analysis: The final HEN is defined, and all the direct exchanges and recirculation proposals have been established.
- 5) Water and energy programs: The strategies proposed for water reutilization are similar to the ones proposed by Asselmann, (1995), Perters et al. (1997), Houle et al (1998), Paris, (2000b) and Bonhivers, J.C et al (2001), but the energy consequences are also analyzed, as well as the efficiency of the washers, paper machine, dryers and heat recovery loops.

The flaw of this methodology is that the thermal composite curves are the basis for all energy and water measures. The modification of the curves after water reutilization is not taken into account. The implementation of isothermal mixing to reduce the surface area of the HEN is correct; however the elimination of existent non isothermal mixing (NIM) points is not envisaged.

Savulescu and Alva-Argaez (2008a) proposed a methodology for the appropriate utilization of non isothermal mixing used for direct heat recovery, to reduce the steam demand. The NIM points should be considered at the data extraction step. NIM points and their thermal relevance are first determined. Then, the NIM-based paths (several NIM points connected) are identified and the temperature profiles evaluated. The final step is the analysis of the thermal efficiency of

the NIM points, the related pinch violations and the redesign of the paths. Brown *et al* (2005) analyzed the process unit operation since the perspective of utilization and production of the required utilities, and the actual requirements of the process. The elimination of NIM points is part of the measures proposed to improve the utilization of the utilities so as to increase the potential for combined heat and power production.

3.4 Exergy analysis

The pinch analysis and water pinch do not consider the efficiency of the equipment and of the production and utilization of the utilities. 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. 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 et al., 1988). The objective is to propose enhancement measures that reduce the exergy destroyed by the way the process operations are performed. There are examples applying this technique in the petrochemical industry (Rivero, 2002; Rivero and Garcia, 2001; Rivero et al., 2004; Sorin et al., 2000; Sorin and Paris, 1999). However, in the P&P industry there are few examples analyzing a complete mill (Gong, 2005), or specific sections (Asselman et al., 1996a; Gemci and Ozturk, 1998; Wall, 1988). There are no cases in the literature where exergy analysis has been combined with other methods, in the P&P industry, for improving the energetic efficiency.

There have been different opinions when trying to define whether pinch or exergy analysis is better. Linnhoff and Alanis (1991) argued that Pinch Analysis has more meaningful targets while also considering design information. Gaggioli et al (1991), on the other hand, established that Pinch Analysis can only be used for designing HEN and, as it is a systematic approach many improvement options can be overlooked by just performing this analysis. Conversely, exergy analysis is able to optimize the targets set by the Pinch Analysis and identifies other kinds of possibilities for improvement. It can be concluded, that those fields of action are different, but complementary. Exergy analysis identifies the operations with poor performances and the

efficiency of the utilities systems, and Pinch Analysis identifies the heat transfer inefficiencies or lack of internal heat recovery.

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. The reduction of exergy lost associated to internal heat recovery was the objective of the study.

Marinova *et al* (2007) used the exergy composite curves (Figure 3-12) in the combined process and utilities analysis. The objective was to determine the exergy destroyed in the production, and distribution of steam, and the cooling water.

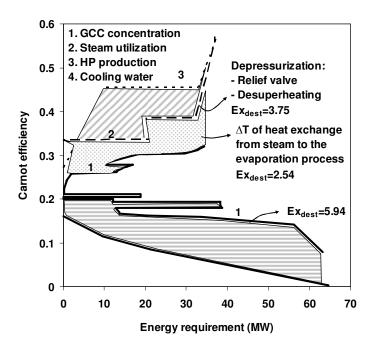


Figure 3-12 Combined process and utilities analysis for a concentration section (Marinova et al.,

Marechal and Favrat (2005) demonstrated the combined used of exergy analysis and process integration techniques to analyse the implementation of utility systems in industrial processes. 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., 1998a) in the computation of the exergetic efficiency (Eq. 2).

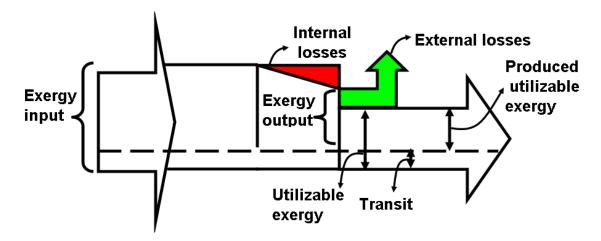


Figure 3-13 Sankey Diagram Exergy flow (Sorin et al., 1998b)

$$\eta_i = \frac{Ex_{out} - Ex_{tr}}{Ex_{in} - Ex_{tr}}$$
3.1

This definition of the efficiency is more representative of what is happening in the process and more accurate (Sorin et al., 1998b) because in addition of the exergy inputs (Ex_{in}) and outputs (Ex_{out}), the exergy that does not suffer transformation, i.e the transit exergy (Ex_{tr}), is also considered. However, a local improvement might have a negative effect on the efficiency of the process (Sorin and Brodyansky, 1992). Therefore, the exergy load distribution method can be used to achieve a global improvement (Brodyansky et al., 1994). This method relates the local exergetic efficiencies of the different process section with the global efficiency, calculating their individual contribution. In the efficiency coefficient the transit exergy Ex_{tr} is taken into account.

This method has been applied in the P&P industry to choose the best option for effluent treatment (Asselman et al., 1996b). It is a tool to correlate energy and water since the exergy is a common measure in both quantities.

3.5 Energy upgrading and conversion

To obtain additional savings after internal heat recovery has been accomplished, it is possible to upgrade low temperature energy sources by means of heat pumps. A heat pump is a mechanical device able to raise the temperature at which a certain quantity of heat is available. There are two principal types: vapour recompression and absorption heat pumps. Absorption heat pumps (AHP) are emerging as a potential alternative to the more common vapour recompression heat pumps (VRHP). The AHP's can upgrade low temperature heat by exploiting the effect of pressure on an absorption—desorption cycle to accomplish the temperature lift from the heat source to the heat sink (Costa et al., 2009). They are thermally driven and when judiciously positioned into an industrial process, they can be operated with practically no purchased power, an advantage over the VRHP.

The positioning of AHP should consider the pinch point (Bakhtiari et al., 2007; Dhole and Linnhoff, 1993; Marechal and Kalitventzeff, 1997; Marinova et al., 2007). The low temperature heat source to be upgraded must be below the pinch point, while the high temperature heat source and the heat sink must be above it. An example of the integration of an AHP in the concentration section of a Kraft process is shown in Figure 3-14.

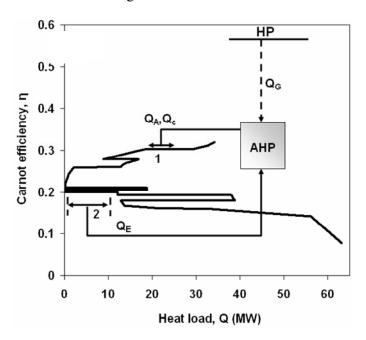


Figure 3-14 Positioning of an AHP

Energy conversion consists of transforming one type of energy into another of better quality or more useful. For instance, thermal energy can be converted into power, by cogeneration, to generate additional revenues. Cogeneration requires the appropriate installation of turbines to drive electric generators. The production and utilization of steam as well as the requirements of the process should be taken into account (Brown et al., 2005; Marechal and Kalitventzeff, 1997; Mateos-Espejel et al., 2007).

Cogeneration units and AHP driven by the steam discharge from the turbine can be combined in trigeneration units. The implementation of such units represents a triple gain to the process: heating and cooling loads are reduced, and power is produced. The implementation of trigeneration involves a two step procedure (Marinova et al., 2007): first, the AHP has to be optimally positioned in the process using the thermal composite curves and then cogeneration is implemented. In the following sections these two steps are summarized.

The turbine is driven by steam from the utility system. It delivers steam at a lower pressure, which is used in part in the process, and in part to drive the absorption heat pump (AHP). A schematic of the AHP coupled to the turbine is given in Figure 3-15a. This unit reduces the net heat demand of the process, supplies electricity to the grid and, reduces the cooling demand. Critical operating parameters of the trigeneration unit are the pressure of the discharge steam and the choice of the process cold and hot streams connected to the heat pump (Figure 3-15b).

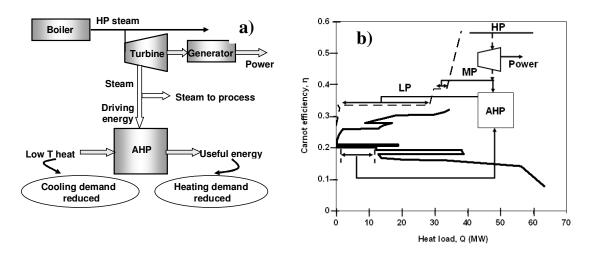


Figure 3-15 a) Schematic of a trigeneration unit b) Positioning of the trigeneration unit in the process

The investment required for this type of units is substantial. However, the increment to the power production potential, in addition to the steam savings generated, can result in substantial revenues.

The interactions between internal heat recovery and the implementation of cogeneration and absorption heat pumps have been the objects of several studies. The potential for power production generated by internal heat recovery to generate additional revenues has also been investigated (Brown et al., 2005; Cakembergh-Mas et al., 2009b; Marechal and Kalitventzeff, 1996a; Marinova et al., 2007; Mateos-Espejel et al., 2007; Mateos-Espejel et al., 2009a).

3.6 Synthesis

The analysis of the energy efficiency is the object of many studies. However, a recurrent problem is the lack of explanation or information of how the data, used for all analyzes, were treated or gathered. Another problem is that the evaluation of the process is either simple or non existent. There are no clear guidelines on how to define a base case and how to evaluate a process for an energy study.

There are several techniques to improve the energy efficiency of a chemical process: internal heat recovery, water reutilization, energy upgrading & conversion, and elimination of non isothermal mixing points. These techniques are typically applied to tackle specific problems or process sections without regard to interactions of the complete process and all issues that affect the energy efficiency.

The studies on energy and water fail to address the problems globally. They are typically applied to water networks. The implications of water reduction projects should be evaluated, as they affect the complete thermal balance of the process.

Exergy analysis is a valuable tool to evaluate the efficiency of a process. However, it has not evolved into a systematic method, such as Pinch Analysis or Water Pinch.

The P&P process are driven by steam and water, therefore, an energy study on this type of process should consider both aspects in the proposition of improvement measures.

3.7 Specific objectives

Based on the information presented, the specific objectives of this thesis are:

- To construct a computer simulation model that represents the energy and water behavior of the process
- To develop a procedure for an in-depth evaluation of the process energy efficiency
- To identify and analyze the interactions between the utilities systems and the process
- To propose a strategy for the implementation of different kinds of improvement measures taking into account energy, technical and economic constraints.

3.8 Overall methodology approach

The methodology consists of four successive stages as shown in Figure 3-16. Each step is a chapter of the thesis (4-7). Chapter 8 presents the complete unified methodology.

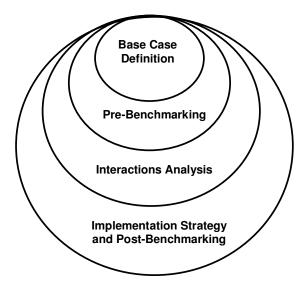


Figure 3-16. Methodology

The inner ring represents the base case definition. A computer simulation focused on the energy and water systems is developed in this step. CADSIM Plus has been used to simulate the process. It is a software specialized in P&P processes, broadly used in Canada. It includes models of all

standard P&P unit operations, typical components and representative operating conditions as default values. ASPEN Water was used to perform data reconciliation on the water system

The second ring corresponds to the benchmarking analysis. The base case is evaluated by three techniques: comparing its efficiency to the current practice of the industry, evaluation of the energy utilization and conversion by the new energy and exergy content indicators, and the determination of the minimum energy and water requirements of the process. The third ring is the core of the methodology; it represents the formulation of technically feasible energy enhancing options. Several techniques are applied in an iterative procedure to cast light on their synergies and counter-actions. The most advantageous solutions are retained. ASPEN HXNET was used to construct the thermal composite curves and for the computation of the heat exchanger network.

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 production of power and the liberation of steam capacity.

CHAPTER 4

BASE CASE PROCESS DEVELOPMENT FOR ENERGY EFFICIENCY IMPROVEMENT, APPLICATION TO A KRAFT PULPING MILL. PART I: DEFINITION AND CHARACTERIZATION

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Keywords: energy efficiency, base-case process definition, utilities systems, simulation, Kraft process, energy optimization, water optimization

4.1 Presentation of the article

This article has been submitted to the Chemical Engineering Research and Design Journal. The paper is presented in two parts. Part I deals with the definition and characterization of an operating Kraft mill situated in Eastern Canada. Part II is a benchmarking analysis of the same process. Part 1 presents the required steps to develop the steam and water systems. Some process inefficiencies are detected. A computer model has been developed, energy and water oriented, and validated for its posterior utilization in more detailed energy analysis.

4.2 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 as the main concern is to solve specific problems without regard to properly defining and evaluating the complete process. The

improvement of the energy efficiency should not only focus on the process but on the utilities systems, i.e. steam and water, as they are the driving forces of the chemical processes. Two stages have been proposed: definition and characterization, and benchmarking analysis. Therefore, the work has been divided in two parts. This paper deals with the first stage. A four-pronged procedure has been developed to properly define and characterize a process for a subsequent in depth energy analysis: data gathering, master diagram, utilities systems analysis, and simulation. The objective of this first stage is to build a computer simulation model so as to provide detailed information on production, distribution, utilization and post-utilization treatment of steam and water utilities. It is also useful to identify process inefficiencies such as the lack of condensate recovery or the presence of non isothermal mixing points. The procedure has been applied to an operating Kraft pulping mill in Eastern Canada.

4.3 Introduction

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 undertaken.

Guidelines and targets that identify process inefficiencies and areas of most likely gains should be formulated at the earliest stage of a retrofit 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 is 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 is presented in Mateos-Espejel et al (2009). The analysis has been based on a novel method which takes into account the interactions and synergies of all systems that impact the energy profile of the optimized process (Mateos-Espejel et al 2009a, 2009b).

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; 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 (Dhole, 1998; El-Halwagi and Manousiouthakis, 1989; Linnhoff, 1993; Wang and Smith, 1994). 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 (Leewongtanawit and Kim, 2008; Mateos-Espejel et al., 2008b; Savulescu et al., 2005a). 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 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 (Blanco et al., 2006; Dahlquist, 2008; Turon et al., 2005)

The case study presented below is an operating Kraft pulping mill located in Eastern Canada. It 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.

4.4 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 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 Figure 4-1.

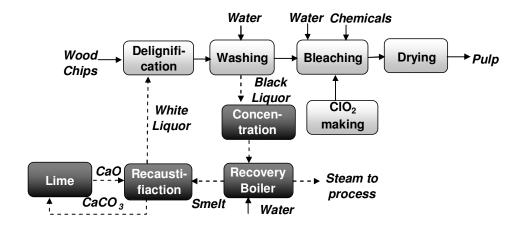


Figure 4-1 Simplified diagram of the Kraft process

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 (ClO₂, H₂O₂, NaOH) at different conditions. The ClO₂ is also manufactured on site. The concentration of the weak black liquor (BL) initially at 15% solids dissolved 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 (dominion) where water is evaporated by indirect heating, and then hot air is used to attain the final specification of pulp consistency (flakt). A steam turbine is used to supply power to drying equipment.

4.5 Methodology

The base process simulation model is constructed in four steps which are described below (Figure 4-2).

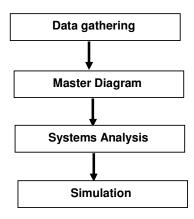


Figure 4-2 Nominal conditions definition and characterization methodology

4.5.1 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 the systems analysis section.

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

4.5.2 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 is 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.

4.5.3 Systems analysis

Water and steam are the driving forces of the material transformations that occur in the process. Therefore, it is important to define both utility systems in detail. In addition, water-energy aspects are analyzed: the various fuels utilization to produce steam, direct or indirect heating, the percentage of condensate recovery, and the water temperature levels.

4.5.4 Computer simulation

The process is simulated in a water-energy oriented perspective to study the interactions between the different systems and evaluate potential energy enhancement measures.

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 or rigorous 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 noise 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.

4.6 Case study

4.6.1 Data gathering

For the 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 selected from this base corresponds to the periods with the highest consumptions; winter for steam and summer for water.

A low and very tolerable discrepancy of 4% (Table 4-1) was found for the steam data averaged over the 2005 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 4-2) but a difference of 34% between water intake and consumption was observed. This large difference is 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 fill the gaps of the overall water balance and perform data reconciliation. These results are presented in the systems analysis sections.

Table 4-1 Average mil	l data for the	overall proc	duction and	utilization of st	team

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

Table 4-2 Average mill data for the overall input and utilization of water

Innut Water

Vol. flow (m³/h)

mput water	V 01. 110 W (111 /11)
Description	Measured data
Treated water	2024.0
Screened water	1072.0
Total	3096.0
Water Utilization	Vol. flow (m ³ /h)
viater Cilization	, on 110 , (111 /11)
Description	Measured data

Description	Measured data
Description Treated	Measured data 1186.3
Description Treated Screened	Measured data 1186.3 861.8

4.6.2 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. Figure 4-3 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 to address the objective of the study: the steam system, the water system, and the process to produce pulp. Water is used for dilution, washing, cooling, and steam production. Steam is used in chemical delignification, to heat up the 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.

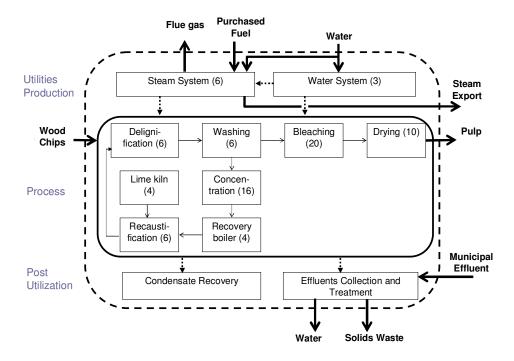


Figure 4-3 Overview of the master diagram.

The master diagram represents 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 compatible with the construction of a representative computer simulation diagram.

4.6.3 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.

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.

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, pulp drying and to entrain a turbine that drives various equipment of the pulp drying machine; the rest is depressurized by pressure release 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 Equation 5.1, results are given in Table 4-3

$$\eta = \frac{\dot{m}^{v} (h_{out} - h_{in})}{\sum_{i} \dot{m}_{i}^{f} HHV_{i}}$$
(5.1)

 η : Efficiency of the boiler (%)

 \dot{m}^{ν} : 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: High heating value (kJ/kg)

Table 4-3. Boiler efficiency and steam production

Boiler	Average (MW)	Max. (MW)	Eff. η (%)	Can. Aver. η ¹ (%)
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. = Efficiency1. from Francis et al (2006)

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 is essentially required to fulfill the requirements of the process; however, 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 (Figure 4-4). 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 its turbine (Figure 4-4). 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 also important to the elaboration of energy efficiency measures. Steam can be either used in direct steam injections or indirect heat exchanges as shown in Table 4-4. The utilization of steam injection eliminates the possibility of condensate recovery.

Table 4-4 Direct or indirect steam utilization by process section

	HP		MP		LP	
	Dir	Ind	Dir	Ind	Dir	Ind
Delignification				$\sqrt{}$		
Bleaching						
Drying		$\sqrt{}$				
Concentration				$\sqrt{}$		
Recaustification						
Deareation						
Water heating						
Boilers						

Dir = Direct heating; Ind =Indirect heating

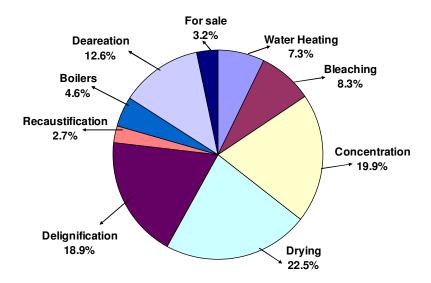


Figure 4-4 Energy consumed by process department as a fraction of the total consumption

Post-utilization

The condensate recovery rate of the process is 46.3% (109.9 t/h) as shown in Figure 4-5. This is below the Canadian average of 75% and 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 impact the efficiency of the boilers, cannot be returned to the steam network but their energy content which is appreciable could be reused to preheat fresh water or other process stream below 100°C.

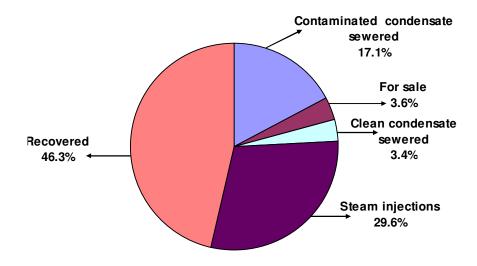


Figure 4-5 Distribution of condensates in the process

The recovered condensates and cold make up water are mixed up and heated by steam injection in the deareator (Figure 4-6). This unit represents 12.6% of the total steam consumption. The amount of steam required depends on the amount of condensate recovered and the temperature of the cold make up water. Therefore, it is important to identify the sections where condensates are not recovered.

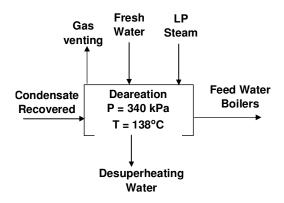


Figure 4-6 Deareation system

Figure 4-7 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

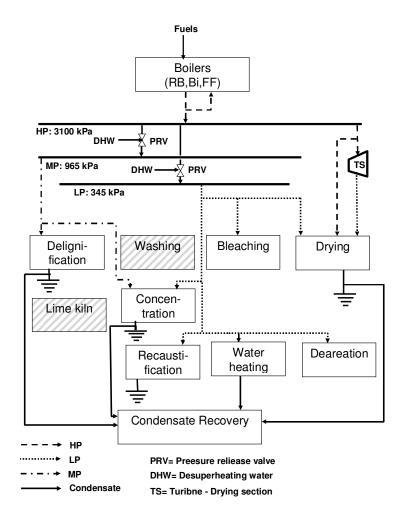


Figure 4-7 Simplified diagram of the production, utilization and post-utilization of steam

Water System

Water is used for a broad variety of purposes such as: 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 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) over the system considered. This can be solved by the least squares method if the formulation is based on linear equations (Jacob and Paris, 2003). 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 based on 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-Aragez (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 m³/h) of the feed water is screened and chemically demineralized for use in operations where it is mixed with the pulp, for example in pulp washing, bleaching and drying or for steam production; it will be referred to as treated water. The remaining 40% (1160 m³/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 ClO₂ making section, and gas washing. Treated cold water is used as make up in the deareator, for the production of ClO₂ which is used as a bleaching agent, 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 stage and for dilution in the pulp drying and chemical production sections.

Figure 4-8 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 (Figure 4-4). 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 sealings, and floor hosing.

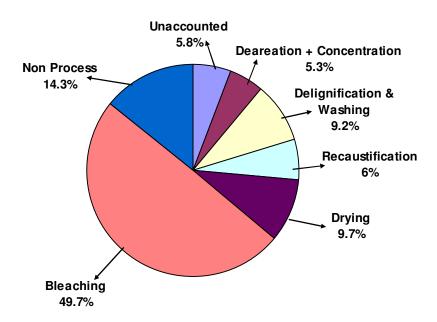


Figure 4-8 Water consumption distribution in the process

Post-process utilization

The post-process utilization of effluents in the Kraft process 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 being 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.

Figure 4-9 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 recover their heat content by heat exchange must be considered.

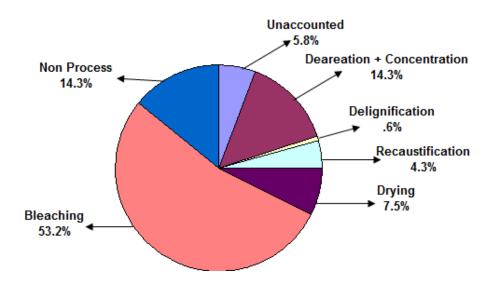


Figure 4-9 Distribution of sewered effluents in the process

Figure 4-10 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.

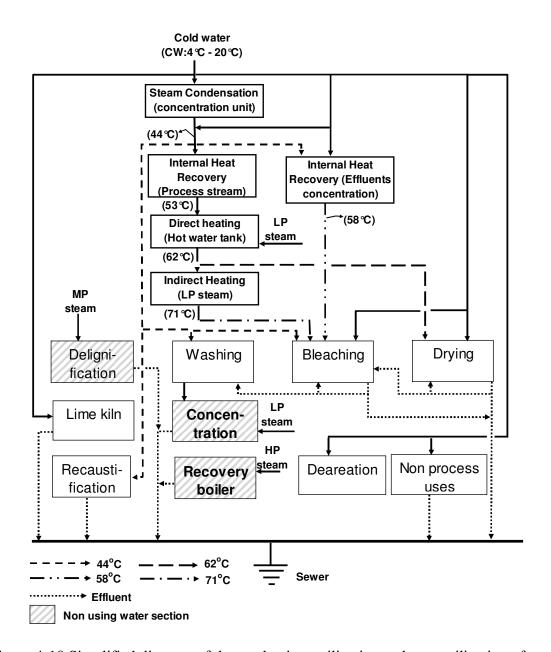


Figure 4-10 Simplified diagram of the production, utilization and post-utilization of water

The overall consumption of steam and water is presented in Table 4-5 and Table 4-6. The measured data values will be compared with the results of the simulation in the next section.

Table 4-5 Steam consumption and condensate recovered by process section

	Stea	Condensate	
	Consum	Recovered	
Process section	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,	0.98	6.4	-
Total process	21.14	272.5	109.9
consumption	21.14	212.3	109.9

Table 4-6 Water consumption by process section

	Water	inputs		ients
Process section	m ³ /adt	m ³ /h	m³/adt	m ³ /h
Water intake				
<u>Treated water</u>				
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 chips	1.6	46.3		
Water evaporated – (flue			1 0	52.6
gases, drying, deareator)	-	-	1.8	32.0
Drying – water out with pulp	-	-	.07	2
Unaccounted	6.4	186.9	6.4	186.9
Total process consumption	110.1	3212.2	110.1	3212.2

Several factors affecting the performance of water and energy systems have been evaluated. Some of them refer to the overall process, such as fossil fuel utilization and cogeneration, and also to specific practices within the systems, for example direct heating, non-isothermal mixing, and effluent reutilization.

- Fossil fuel utilization. The need of fossil fuel in the process is caused by either the low efficiency of the boilers or 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 injections 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, 2008b). 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 (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.

4.6.4 Computer simulation

CADSIM Plus has been used to simulate the process. It is a software specialized in P&P processes, broadly used in Canada. It includes 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).

Simplifications and Required Level of Details

The utility systems have been simulated in detail (Figures 9 and 10). 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 4-5). Missing information and non matching boundary data required to define the simulation were computed by partial heat and mass balances. Several simplifications were introduced:

- Combining or regrouping of 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.

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

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.

55

An Excel spreadsheet was used to transfer parameter values to the simulation (T, P, flowrates)

and to extract data for posterior analyses. These features help 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

PRV's: target pressure

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 and,

condensate recovery. More than 130 individual pieces of equipment have been simulated:

digester, tanks, washers, dryers, evaporators, flashes, 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.

Simulation Validation

The difference between measured and computed values for the production of steam is .9% (Table 4-7). All individual steam-using operations have differences below 10%. Table 4-8 shows a difference of 6% between the computed water intake and the measured value.

Table 4-7 Overall production and utilization of steam

	Mass flow (t/h)			
Steam production	Simulated data	Measured data	% diff.	
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	

	Mass flow (t/h)			
Steam utilization	Simulated	Measured	% diff.	
Steam danzation	data	data	70 dill.	
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	

Table 4-8 Water intake and utilization

	Volumetric flow (m ³ /h)				
	Simulated	Measured	%		%
Water intake	data	data	diff.	PID	diff.
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		

	,	Volumetric	flow (n	n³/h)	
	Simulated	Measured	%		%
Water utilization	data	data	diff.	PID	diff.
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	-			

4.7 Conclusions

A procedure for the appropriate definition and characterization of a base case in a water-energy oriented perspective has been proposed. As a result the nominal conditions of the process have been established. The sources of information were measured data, and the PID's. The construction of a master diagram resulting of encompassing 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 aspects 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 set the basis for water and energy analysis. Part II presents the benchmarking of the case study, where 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.

4.8 Acknowledgements

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CHAPTER 5

BASE CASE PROCESS DEVELOPMENT FOR ENERGY EFFICIENCY IMPROVEMENT, APPLICATION TO A KRAFT PULPING MILL. PART II: BENCHMARKING ANALYSIS

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Keywords: benchmarking analysis, energy efficiency, Pinch Analysis, Water Pinch, Exergy analysis, Kraft process

5.1 Presentation of the article

This paper has been submitted to the Chemical Engineering Research & Design Journal. A new benchmarking procedure has been developed to evaluate the current energy efficiency of the process. It consists of 5 phases: data compilation, comparison to the industrial practices, utilization of new energy and exergy content indicators, targeting by Pinch Analysis and Water Pinch, and a Synthesis. The synthesis step gathers all information necessary for evaluating the energy efficiency the process. The interactions between the process systems are also highlighted. Guidelines for the posterior energy analyzes are established

5.2 Abstract

A new procedure for benchmarking analysis has been developed to evaluate in detail the energy efficiency of a chemical process. Benchmarking must be performed to identify the inefficiencies of the process before proposing energy enhancement measures. All process sections and the utilities systems, i.e. steam and water, are evaluated. Five phases are required. The first phase consists of gathering all data necessary to perform benchmarking and to support advanced steam and water analyses. The second phase represents the evaluation of the base case process by a comparison of its efficiency to the current practice of the industry. The third stage uses new energy and exergy content indicators to analyze the efficiency of the production, distribution and utilization of the utilities. The fourth phase is the targeting by Pinch analysis and Water Pinch so as to determine the minimum energy and water requirements of the process. The last phase is a synthesis where main results are analyzed to establish the inefficiencies and the limits of the possible improvement. Issues associated to the interactions between the utilities systems and the process should also be considered. The procedure has been applied to an operating Kraft pulping mill in Eastern Canada.

5.3 Introduction

An approach to the definition and characterization of the base case model of an operating process has been presented in Part I of this paper. It has been applied to an operating Kraft pulping mill. The model was specifically designed to support an in depth energy analysis of the mill, it has been implemented as a steady state simulation on the CADSIM PLUS® software. It is focused on the steam and water systems. Both utilities are traced rigorously from production (for steam) or preliminary treatment (for water), through their distribution, utilization and post-utilization fate: recovery, reutilization, and eventual reject to the environment. The simulation generates mass balances (water, fiber and total dissolved solids) as well as heat balances on all the major unit operation and for the global process and its principal sectors.

Part II of the paper presents a fundamental analysis which must be performed before the development and evaluation of energy enhancing measures is undertaken. This analysis is the process benchmarking. The object of this task is to asses the current energy performance of the

process globally and by sector in order to identify areas of inefficiencies and to establish enhancement targets. Benchmarking can also be used to identify where the most likely energy gains can be obtained and to guide engineering efforts.

5.4 Literature review

The pulp and paper (P&P) industry is among the largest industrial consumers of energy and water. Rising energy costs and more stringent environmental regulations have led the industry to refocus its efforts towards identifying ways to improve energy and water conservation. In a typical Kraft process, the larger the amount of water consumed and effluent produced, the larger will be the energy required for heating, cooling and pumping. The evaluation of a process before implementing enhancement measures is often based on a comparison of its efficiency to that of other similar processes by the utilization of performance indicators (Francis et al., 2004).

The utilization of performance indicators as a benchmarking tool is common practice to measure the variability and correct the operation of the process. Lang and Gerry (2005) used indicators to monitor control systems by identifying the periods where control loops are out of normal mode or oscillating. Buckbee (2007) defined indicators such as the ratio between the set points and the actual targets achieved. Van Gorp (2005) proposed a methodology where the ratio of the steam consumption of a unit and the final product tonnage were compared to the goals set by the energy reduction projects. A mathematical relation is used to target the potential energy consumption, which is compared with the actual. Retsina (2006) suggested a similar methodology, with the same type of indicators, adding a real-time analysis to identify gaps between target and actual values so as to take measures to maintain the energy efficiency of the process. Retsina (2005) has also developed a software for monitoring the indicators of different processes. However, there are no indicators that reflect the causes of possible inefficiencies such as the equipments maintenance, internal heat recovery or water reutilization.

Performance indicators of the internal heat recovery should encompass aspects that reflect the excess steam utilization. This is the case of the energy content of the hot effluents and flue gases. The more energy rejected in these heat sources the more hot utility will have to be supplied to the process. Furthermore, the excess water utilization is also reflected in the production of effluents.

All chemical processes respect the law of conservation of energy. However, this law does not take into account the degradations that occur in irreversible processes. 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. Exergy can also be used as an indicator of process inefficiencies, although it rarely is.

The improvement of the energy and water efficiencies is typically performed individually by the application of Pinch Analysis[®] and Water Pinch (Jacob et al., 2002; Koufos and Retsina, 1999; Koufos and Retsina, 2001; Noel, 1995; Noel and Boisvert, 1998). Pinch Analysis® is used to determine the minimum heating and cooling requirements to be supplied by utilities (Linnhoff et al., 1994a; Smith, 1995). The basis is the display in a temperature vs enthalpy diagram of all possible heat transfers within the process. It consists of the hot and cold composite curves, which respectively represent the heat availability and demand in the process. Water Pinch is used to determine the minimum water requirements and minimum effluent production. El-Halwagi et al (1989) have first proposed a method which is a direct extension of thermal pinch based on the analogy between heat and mass exchanges. Shafiei et al (2003) analyzed different applications of this method depending on the type of water using operations. Wang and Smith (1994) have proposed a method for networks of washing operations of organic process streams immiscible with water. Dhole (1998) proposed another approach for single phase processes (as the Kraft process), generally water based, where the main streams content of the desired product are enriched by reducing the level of contamination through a succession of operations, such as dilution, displacement and thickening. The basis is the representation in the purity vs mass flow rate diagram of the aggregate of all possible mass transfers between water streams. It consists of two composite curves, one for water sources and the other for water sinks, which respectively represent the effluents produced and water demand in the process. However, these individual analyses ignore the interactions between the water and steam systems and this may result in counter productive measures and increased energy cost (Mateos-Espejel et al., 2008b). The development of improvement scenarios with regards to energy and water issues could lead to more attractive projects, because appropriate water reutilization reduces the surface area needed for increasing internal heat recovery (Savulescu et al., 2005b).

A benchmarking procedure has been developed to evaluate the process to increase its energy efficiency. The procedure evaluates energy, water and exergy aspects of the process. It incorporates new performance indicators based on the energy and exergy content of the effluents and flue gases, the exergy required by the process and supplied by the utilities and, water utilization. A targeting step involves the utilization of the thermal and water composite curves to determine the maximum heat recovery and water reutilization theoretically possible. In addition the conventional comparison to the current practice is also performed.

5.5 Methodology

The benchmarking procedure developed in this work is summarized in Figure 5-1.

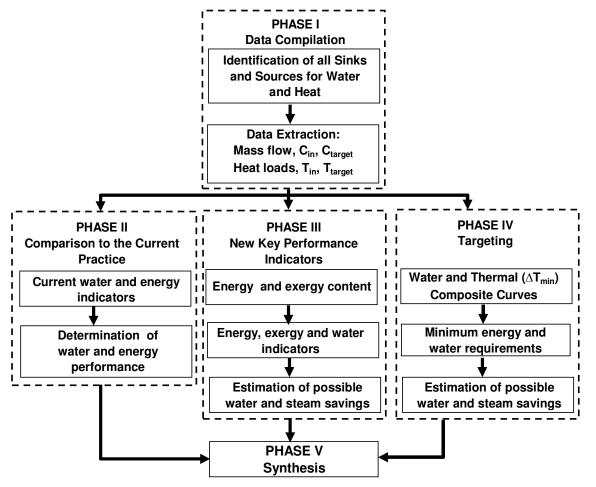


Figure 5-1. Methodology

The objective of this benchmarking procedure is to combine different methods for evaluating the energy and water efficiency so as to identify process inefficiencies and to establish guidelines for developing effective energy improvement measures. Specifically the procedure will assist in the identification of:

- The unit operations with poor energy performance
- The maximum water reutilization and energy recovery theoretically possible
- The efficiency with which the thermal energy is produced and used in the process.

5.5.1 Phase I Data compilation.

This phase consists of gathering all the data necessary to perform the benchmarking analysis. This information will be later be used for energy and water analysis and simultaneous optimization. Phase I is done in two steps. First, all sources and sinks for both heat and water are identified. Heat sinks, or cold streams, are streams that need to be heated by means of a hot utility or by internal heat recovery. Heat sources, or hot streams, are streams that can be cooled down and should be, whenever this is possible, put their heat content to good economic use. Water sources designate the streams that can be re-used or that are process effluents. Water sinks are the operations where water is required.

For the thermal analysis, all steam users and the streams involved in internal heat recovery measures are identified. The streams which are part of non isothermal mixing (NIM) points, including direct injections of steam, are also taken into account. For the water analysis, all fresh water users and the streams involved in water reutilization measures are identified.

The second step consists of determining the temperature and heat loads for all cold and hot streams. In the case of the cold streams to be heated by steam, the target temperature is the temperature of the condensing steam. For the water streams, it is important to determine the contaminants that affect the operation of the process or the quality of the product. The maximum contaminant concentration allowed by the water sinks is obtained by analyzing the operation of the process as recommended by Foo et al (2006).

This approach to do data extraction ensures that of all streams that have an effect on the thermal and water performance of the process are taken into account.

5.5.2 Phase II Comparison to the current practice.

The comparison of specific characteristics of a process to the average practices is done to identify inefficient sections. The following key performance indicators (KPI), normalized to the pulp production rate are used for the comparison. They apply to the overall process and to the individual sections:

- Steam consumption
- Water consumption
- Effluent production
- Thermal production of the recovery boilers
- Net thermal deficit i.e. the difference between the overall steam consumption and the steam production by the recovery boilers)

5.5.3 Phase III New key performance indicators.

New indicators have been added to the previous ones to take into account the energy and exergy content of effluents and flue gases as these variables reflect the excess utilization of steam by the process. Table 5-1 gives the new energy and exergy indicators.

Energy indicators. Indicators that relate the energy content of effluents and flue gases to the steam produced by the boilers (E_{SP}) have been defined, they are EC_E and EC_{FG} . EC_T represents the total energy rejected. The steam required for heating water is given by EC_{WTot} . The target temperature for the effluents is that of the treatment plant (T_{ET}). For the flue gases the target is the temperature of the sulfuric acid condensation (T_{SAC}), below which the gases must not be cooled to avoid the formation of this corrosive acid from the SO_3 present.

Exergy indicators. Exergy content is used because it involves the quality and quantity of the energy produced, used and wasted. The exergy content is defined as the heat load (Q) multiplied by the Carnot coefficient (η). Exergy composite curves of the steam production and utilization and, of the current process requirements are built to quantify the exergy destroyed. Sankey diagrams of the exergy balances are used to identify the exergy lost, and the useful exergy supplied to the process. Estimates of the potential increase of internal heat recovery, of water reutilization and of cogeneration are computed from those KPI.

The destruction of exergy is associated with the irreversible transformation that occurs in the process. Exergy is destroyed in the heat exchangers because of the temperature difference between hot and cold streams or by the adiabatic expansion of steam in a valve. The exergy which is no longer useful or available for the process is considered lost; it encompasses the streams vented or sewered, the flue gases or losses to the environment. Reduction of the exergy destroyed and lost can be accomplished by internal heat recovery, effluents reutilization, cogeneration and energy upgrading.

The exergy destroyed is a measure of the lost potential for energy conversion into power. An indicator to quantify this potential has been defined as ExC_{EC} ; it is the ratio between the total exergy destroyed and the exergy supplied to the process (Ex_{SP}) . Indicators that relate the exergy content of effluents and flue gases to the exergy required by the process (Ex_{Proc}) have been defined, they are ExC_E and ExC_{FG} . ExC_T represents the total exergy rejected. The exergy required for water heating is given by ExC_{WTot} .

Table 5-1 New KPI

Name	Symbol	Equation	
Energy indicators			
Energy rejected in effluents,	EC_E	$mC_p (T-T_{ET})/E_{SP} $ (6.1)
Energy rejected in flue gases, Total energy rejected, Energy for heating water,	$\begin{aligned} &EC_{FG}\\ &EC_{T}\\ &EC_{WTot} \end{aligned}$	$EC_E + EC_{FG}$ ((6.2) (6.3) (6.4)
Exergy indicators			
Energy conversion,	ExC _{EC}	$(Ex_{dest, HP prod} + Ex_{dest, PRV's} + Ex_{dest, THX})/I$	Ex _{SP} (6.5)
Exergy rejected in effluents, Exergy rejected in flue gases, Total exergy rejected, Exergy for heating water,	$\begin{aligned} ExC_E \\ ExC_{FG} \\ ExC_T \\ ExC_{WTot} \end{aligned}$	$\begin{array}{ll} mC_p \left(T-T_{ET}\right) \eta_E / Ex_{Proc} & (6) \\ mC_p \left(T-T_{SAC}\right) \eta_{FG} / Ex_{Proc} & (6) \\ ExC_E + ExC_{FG} & (6) \end{array}$	6.6) 6.7) 6.8) 6.9)

5.5.4 Phase IV Targeting.

The thermal and water composite curves, obtained by thermal and water pinch analyses, are constructed to determine the minimum energy and water requirements as well as the maximum internal heat recovery and water reutilization that can theoretically be accomplished.

5.5.5 Phase V Synthesis.

The main results are analyzed to determine the causes of the inefficiencies and the limits of possible improvements. Energy-water interactions between the utility systems and the process are presented.

5.6 Case study

The benchmarking procedure has been applied to an operating Kraft mill situated in Eastern Canada. The process and its utility systems have been described in detail in Part 1.

The mill uses an eight batch digester sequence for chemical delignification and a five stage bleaching sequence which uses different bleaching agents (ClO₂, H₂O₂, NaOH) at different conditions (Figure 5-2). Before stage 1 there is a pre-washer whose effluent is partly reused in the

washing section. Part of the effluents of the last three stages is reused; whitewater from the pressing section of the pulp machine is used in the last stage washer. Steam is injected after stages 1, 3 and 4.

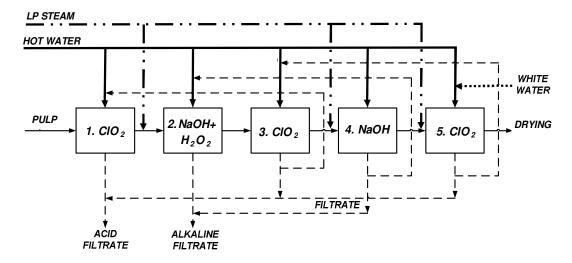


Figure 5-2 Bleaching section

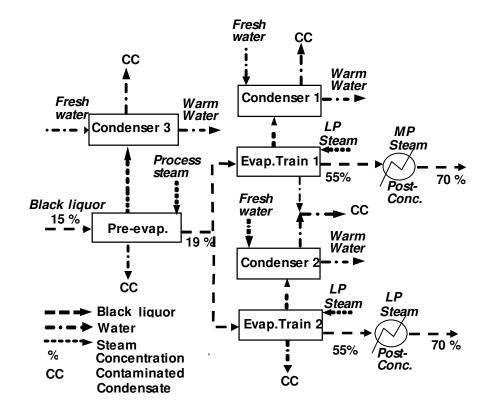


Figure 5-3 Black liquor concentration section

The weak black liquor, BL, at 15% dissolved solids concentration, DSC, is concentrated in two steps (Figure 5-3); first, it is passed through a set of pre-evaporators driven by recycled steam to reach 19% DSC, and then it is split between to two parallel evaporator trains, where it is concentrated to 55 % DSC, with post-concentrators where it reaches 70% DSC. Both trains and the post concentrator are driven by live steam. The water evaporated in all equipment is condensed (contaminated condensates) after each train by fresh water which is later reused in the process.

Drying is performed in two steps: first, the pulp sheet passed by a set of cylinders (dominion dryer) where water is evaporated by indirect heating, and then hot air is used to attain the final specification of pulp consistency (flakt dryer).

5.6.1 Phase I Data compilation

A stream ID, attached to each stream, consists of a character segment and a number. The character segment refers to the process section with which the stream is annotated. The streams involved in NIM points have been highlighted.

Table 6-A1 and 6-A2 (in the annex) show the cold and hot streams respectively. The operations where steam cannot be replaced are stripping, soot blowing, recaustifaction, chemical preparation and the steam exported.

Table 6-A3 and 6-A4 show the water sinks and sources. The concentration of dissolved solids in the water, which includes the organic and inorganic by-products from the chemical delignification of wood, is a constraint to be satisfied by the water sources. Some streams have already been thermally defined for the energy analysis (process effluents and hot water requirements). The fact that some streams are involved in both energy and water analysis underscores the importance of energy-water interactions.

5.6.2 Phase II: Comparison to current practice

Two sets of data have been used, one corresponding to the maximum utilization of steam (winter) and one corresponding to maximum water consumption (summer). The steam and water usage is

mainly affected by the temperature of the water intake (river). That temperature varies from \sim 4°C in winter to \sim 20°C in summer. The pulp production of the mill is essentially constant throughout the year.

Thermal Energy Consumption

An energy survey conducted at 49 P&P mills (Francis et al., 2006), 47 Canadian mills, 24 of which are Kraft processes and two from the United States has been used as source of data for this task. The results are shown in Figure 5-4 and 5. The indicators used to analyze the global efficiency by section are normalized to a unit of production, the oven dried ton (odt) which is the habitual unit in the industry. Other values used are given in terms of air dried ton (adt), i.e. the material dried in the ambiance. The difference in values expressed in both units is generally about 5%. During the summer the steam consumption is reduced by about 10%.

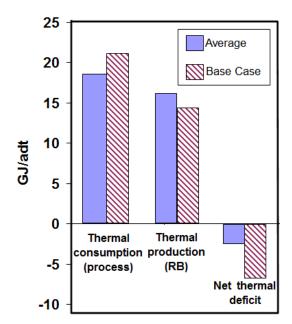


Figure 5-4. Overall thermal consumption and thermal energy production

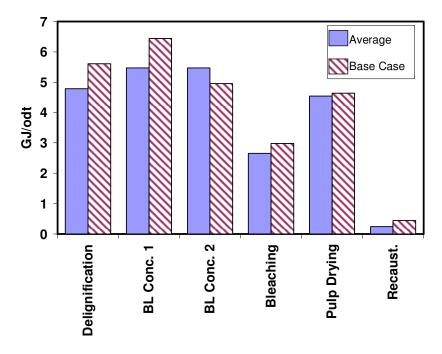


Figure 5-5. Thermal consumption by process section

The global consumption and the net thermal deficit are above the average (Figure 5-4). The net thermal deficit is a consequence of poor efficiencies of recovery boilers and excess steam required by the process. It is compensated by the substantial steam production by fossil fuel and biomass. In principle, the recovery of the heat content of the concentrated BL should cover the process needs for steam (McIlroy and Wilczinsky, 1999). Figure 5-5 indicates that the emphasis of the analysis should be put on three sections: delignification, the BL concentration train 1 and the pulp bleaching, which have consumptions above the Canadian average. These sections are likely to represent, low cost energy saving opportunities.

Water usage

The data used for comparison is the average practice for a Canadian Kraft mill in the 1990's, (Gullichsen and Fogelholm, 1999; Turner, 1994). They encompass total water consumption without regards to pre-usage treatment. The indices for water consumption and effluent produced are both standardized to the pulp production rate in adt. During the summer the overall water consumption increases by 18% because of the need for chilled water to produce on site the ClO₂ used as the bleaching agent.

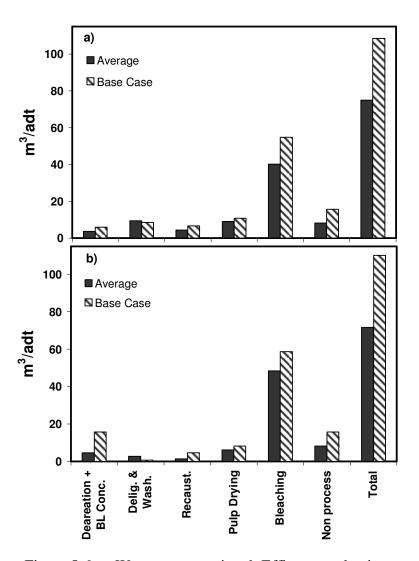


Figure 5-6. a: Water consumption; b:Effluent production

Figure 5-6 shows that the water consumption is superior to the Canadian average for practically all departments. This reveals a lack of water reutilization within the process principally from the BL concentration and bleaching sections. The usage of steam by the bleaching section is also excessive as shown in Figure 5-5. The BL concentration section has high energy consumption and produced about three times the Canadian average amount of sewered effluents. Particular attention will be given to water usage for cooling in the ClO₂ making unit, which is part of the bleaching section consumption. The need for cooling water could probably be reduced by increased internal heat recovery.

Remarks

The identification of the inefficient sections of the process is an important first step in the analysis. However, the cause of those inefficiencies cannot be determined at this stage. The quality of the thermal energy as it is produced, used and eventually rejected provides further insights in the matter. This can be done by means of other KPI as discussed in the next section.

5.6.3 Phase III New key performance indicators

The exergy composite curves have been constructed (Figure 5-7) to show the exergy destroyed from production of energy by the combustion of fuels to its utilization by the process. Primary energy, produced by fuels combustion, is used to generate intermediate energy levels in the form of HP, and subsequently MP and LP steam.

- Area 1: exergy destroyed by the HP production
- Area 2: exergy destroyed by the adiabatic expansion and desuperheating to produce MP and LP steam
- Area 3: exergy destroyed by the heat exchange between live steam and the process sinks.
- Area 4: exergy currently required by the process

The sum of Areas 1 to 4 represents the exergy supplied by the combustion of fuels in the boilers $(Ex_{SP} = 121.5 \text{ MW})$. The exergy currently required by the process Ex_{Proc} (Area 4) is only a small fraction of the supply (39%). The adjustment of the steam pressure levels would reduce the amount of destroyed exergy (Area 3).

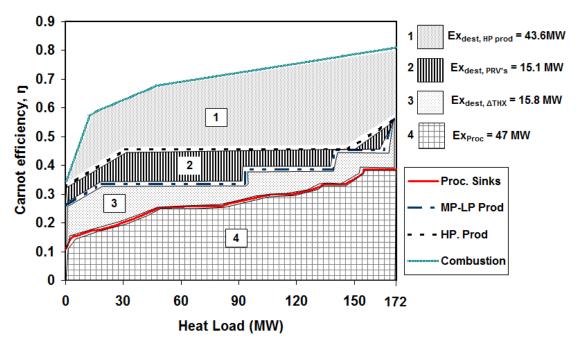


Figure 5-7 Exergy composite curves of the current process

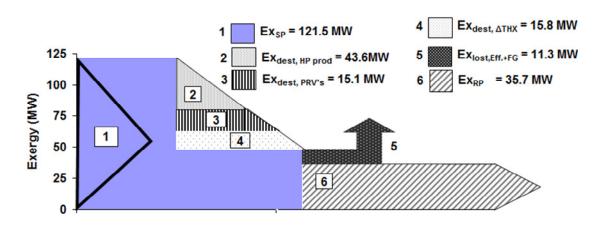


Figure 5-8 Sankey diagram of the exergy heat flows supplied to the process

Figure 5-8 is a Sankey diagram of the exergy flowing through the process.

- Flow 1: total exergy supplied by the combustion of fuels.
- Flow 2: destroyed exergy because of the production of HP steam.
- Flow 3: destroyed exergy by the adiabatic expansion in the PRV's for the production of MP and LP steam.

- Flow 4: destroyed exergy by the heat exchange 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

Flow 5 and 6 represent the total exergy currently used by the process (Ex_{Proc}). The recovery of the exergy lost by means of internal heat recovery or water reutilization would reduce the need of steam and consequently the requirement of primary energy.

Figure 5-9 shows the Sankey diagram of the exergy supplied to produce hot water.

- Flow 1: exergy supplied by steam
- Flow 2: exergy destroyed by heat exchange between live steam and water.
- Flow 3: exergy required for producing hot water.

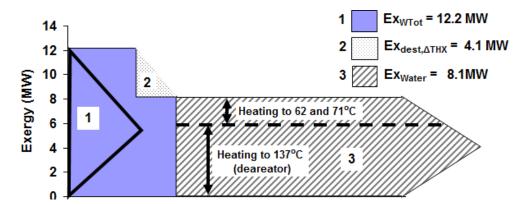


Figure 5-9 Sankey diagram of the exergy supplied for producing hot water

About 34% of the exergy supplied for water heating is destroyed. The effect of water reutilization measures would not only reduce the exergy destroyed but also the steam required in this operation.

Table 5-2 gives the energy and exergy content required to compute the new KPIs presented in Table 5-3.

Table 5-2 Energy and exergy data for the nominal process

	Energy	Exergy
	Content	Content
	(MW)	(MW)
Fuels combustion (Ex _{SP})	172	121.5
HP steam production	172	78
Steam utilization	172	62.8
Process consumption	172	47
(Ex_{Proc})	172	47
Flue gases	11.8	4
Hot effluents	44.9	7.3
Water heating (Ex _{WTot})	37.1	12.2

Table 5-3 Exergy and energy indicators for the nominal process

Name	Value
	(GJ/GJ)
Energy	
indicators	
EC_E	.26
EC_{FG}	.07
EC_T	.33
EC_{WTot}	.22
Exergy	
indicators	
ExC_{EC}	.61
ExC_E	.16
ExC_{FG}	.09
ExC_T	.25
ExC_{WTot}	.26

Indicators analysis

The exergy destroyed in the process accounts for 61% of the total exergy supplied. This value represents the lost potential for energy conversion. The exergy destroyed in heat exchangers cannot be totally eliminated but can be minimized by the adjustment of the steam pressure levels and the improvement of the boilers efficiency. The implementation of turbines eliminates the exergy destroyed by the PRV's.

The possibility of improvement by internal heat recovery or energy upgrading accounts for 25% (ExC_T) of the exergy required by the process (Ex_{Proc}) . The exergy indicator of the flue gases (ExC_{FG}) has a greater value than the corresponding energy indicator (EC_{FG}) , because the high temperature of the flue gases increases the quality of their energy content. In contrast, the exergy indicator of the effluents (ExC_E) is lower than the corresponding energy indicator (EC_E) because the effluents have near ambient temperature. The energy used for water heating accounts for 22% (EC_{WTot}) of the total energy required by the process. The exergy required for water heating, 34% of which is currently destroyed (Figure 5-9), can be supplied by other heat sources at lower temperature than steam.

Remarks

The new KPIs are a complement to the comparison to the current practices, because quantify several aspects of the energy efficiency of the process:

- Exergy wasted (lost or destroyed)
- Production and utilization of steam
- Potential for cogeneration
- Energy-water issues (exergy and energy required to heat up water).

Nevertheless, the analysis of all sinks and sources for water and heat is needed to establish the limits to improving internal heat recovery and water reutilization.

5.6.4 Phase IV Targeting

Pinch Analysis

A ΔT_{min} of 10°C has been used in previous P&P studies (Savulescu and Alva-Argaez, 2008b) as recommended by Linnhoff-March (1998). The variation of the heating requirement with respect to the ΔT_{min} was analyzed to verify that this value is adequate for this study. The current process,

which consumes 172 MW of hot utility, corresponds to a ΔT_{min} of 30°C (Figure 5-10). The variation of the heating requirement is most sensitive between 5°C and 40°C and much less below 5°C, however the capital costs increase rapidly at lower ΔT_{min} (Kemp, 2007). Therefore, the ΔT_{min} of 10°C was used to construct the composite curves (Figure 5-11). The minimum heating requirement (MHR) is 123 MW, the minimum cooling requirement (MCR) is 10 MW and the pinch point (PP) is at 71°C. The maximum internal heat recovery that the process can achieve is 192 MW. (Linnhoff-March, 1998).

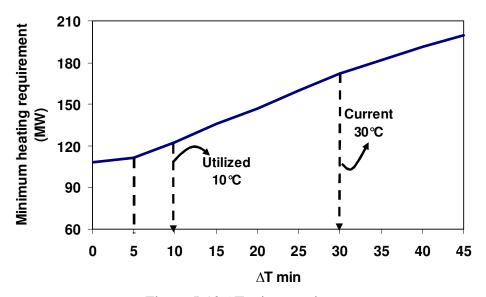


Figure 5-10 ΔT min targeting

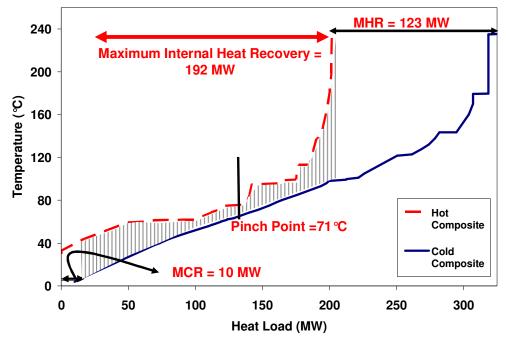


Figure 5-11 Thermal composite curves of the process

The difference between current steam consumption (172 MW) and MHR (123 MW) is the maximum amount of steam that could be saved (49 MW or 29% reduction) by the increasing internal heat recovery. Additional savings could be obtained by upgrading the energy of the heat rejected, after maximizing internal heat recovery.

Heat recovery measures have already been implemented by the mill and are shown in Part I. An analysis of pinch rules violations should be performed to asses the actual efficiency of these measures.

The water temperature rise during summer reduces the steam consumption (10% overall). As the requirement for heating water is also decreased, part of the heat load for steam condensation in the BL concentration section (BLC10, BLC13, BLC14 in Table 6-A2) becomes an additional cooling need (22 MW) in summer. This will be taken into account when proposing measures for increasing internal heat recovery.

5.6.5 Water reutilization

The water composite curves are shown in Figure 5-12. The pinch point is located at DSC = 0 ppm. The minimum water consumption (MWC) is $1000 \text{ m}^3\text{/h}$ and the minimum effluent production (MEP) is $880 \text{ m}^3\text{/h}$. The maximum water reutilization that can be achieved is $1360 \text{ m}^3\text{/h}$. Thus, the process could theoretically reduce its overall consumption by 31%. The implementation of external purification devices to further reduce the DSC of the water sources would be needed to increase water savings.

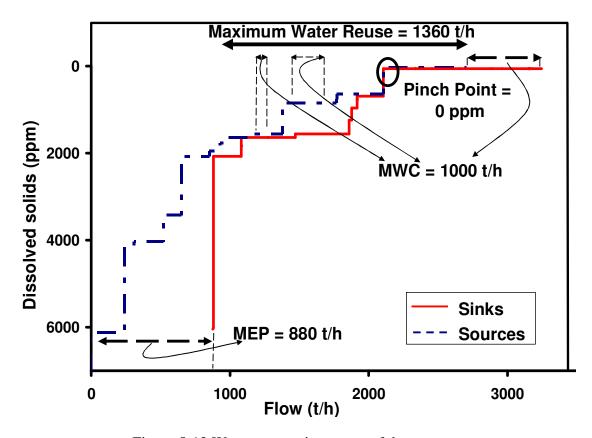


Figure 5-12 Water composite curves of the process

Remarks

The water and thermal composite curves are interconnected through the requirement of fresh water intake and the amount of effluents rejected. The development of water reutilization and internal heat recovery measures must consider energy and water issues simultaneously.

5.6.6 Phase V. Synthesis

The steam and water consumptions are above the Canadian average practice. The BL concentration 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 low level of internal heat recovery and water reutilization. The 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 the water and energy systems, the interactions between the two approaches should be identified before formulating energy saving measures. Water reutilization projects will reduce the steam utilization since water heating represents 22% of the total consumption. All these issues are interrelated and cannot be tackled individually. Interactions analysis which considers all the inefficiencies encountered during the base case definition will be performed.

5.7 Conclusions

The three methods used to evaluate the energy and water performance, complement each other to obtain a detailed perspective of the process inefficiencies. The interactions between the utilities systems and process units have been identified as well as the possible limits of internal heat recovery and water reutilization have been identified.

The exergy content indicators characterize the efficiency of the production and utilization of steam, and the importance and quality of the heat sources currently wasted. The targeting step sets the limits of the potential energy efficiency enhancements. It gives a perspective on interactions between steam and water systems.

The following guidelines can be formulated.

• The analysis of the interactions between the process systems should be conducting prior to developing improvement measures. The effects of water reutilization measures on the MER

and pinch point should be determined. The new KPIs can be used to asses the effects of water reutilization and internal heat recovery in the overall energy efficiency.

- The analysis of the operating conditions of BL concentration, and pulp bleaching sections is required before applying internal heat recovery measures.
- The evaluation of the efficiency of non isothermal mixing points in the process can be done by analyzing the associated exergy destroyed.
- Energy upgrading, and condensate recovery must be evaluated to obtain further steam reductions.
- The implementation of cogeneration to produce power will reduce the exergy destroyed in the PRV's.

The benchmarking analysis establishes the efficiency of the base-case process, and that is the basis for the interactions analysis.

5.8 Acknowledgements

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5.9 Annex

Table 6-A1. Cold streams

Stream ID	Description	T start (°C)	T target (°C)	Heatload (MW)
BLC1	Water – Cond. 3	4.0	61.7	32.7
BLC2	Water - Cond. 1	4.0	44.2	13.6
BLC3	Water- Cond. 2	4.0	44.2	12.5
WP1	Make up water-warm water tank (NIM)	4.0	44.2	7.5
WP2	Water - 58℃	4.0	58.0	7.6
WP3	Water - 58℃	44.2	58.0	2.9
WP4	Water heating	44.2	53.3	8.7
WP5	Water - 62 °C (NIM)	53.3	62.0	8.3
WP6	Water - 71 ℃	62.0	71.0	5.6
DEL 1	Delignification	63.2	170.0	32.4
DEL 2	Contaminated water (NIM)	60.2	93.4	22.4
DEL 3	Wood chips to delignification (NIM)	4.0	63.2	4.1
BLEA 1	Stage 1 - steam mixer (NIM)	49.5	56.0	2.0
BLEA 2	Stage 3- steam mixer (NIM)	68.6	75.0	2.9
BLEA 3	Stage 4- steam mixer (NIM)	71.9	85.0	2.6
DRY 1	White water direct heating (NIM)	62.1	63.1	2.8
DRY 2	Dryer-hot air	78.0	160.0	21.8
DRY 3	Dryer – indirect heating	100.0	101.0	7.7
DRY 4	Whitewater - reheating	38.0	60.0	4.0
BLC4	BL - train pre-evap	63.4	78.0	4.3
BLC5	BL - PC train 1	101.4	127.8	7.4
BLC6	BL - train 1	121.8	122.8	9.6
BLC7	BL - PC train 2	104.9	132.2	8.9
BLC8	BL - train 2	98.2	99.2	11.9
BLC9	Water heating pre-evap	80.3	96.0	10.2
DEA 1	Cold water to deareator (NIM)	4.0	57.1	7.1
DEA 2	Deareator (NIM)	57.1	137.7	23.2
LP 1	REC, Chem. prep, aux. equip.	143.4	143.5	12.5
MP 1	REC, Stripper, sawmill	179.4	179.5	13.1
HP1	Soot blowing, aux, equip.	235.0	235.1	5.9

WP = water preparation; DEL = delignification; BLEA = bleaching; DRY = drying; BLC = black liquor concentration; DEA. = dearator; BOIL = boilers; Cond. = condenser; PC= post concentrator; REC = recaustification; CC = contaminated condensate; Chem. Prep = Chemical preparation

Table 6-A2. Hot streams

Stream ID	Description	T start (°C)	T target (℃)	Heatload (MW)
WP 6	Warm water from Cond. 3 (NIM)	61.7	44.2	10.3
WP 7	Contaminated water to heat water	72.9	60.0	8.7
WP 8	Flashed steam - delignification (NIM)	138.3	137.3	1.0
WP 9	Warm water tank overflow	58.0	33.0	0.9
DEL 4	White liquor to delignification (NIM)	85.0	63.2	2.2
DEL 5	Pulp recycled to delignification (NIM)	81.0	63.2	1.6
DEL 6	Flash steam-blow down tank (NIM)	96.0	93.4	22.4
DEL 7	CC	96.1	33.0	1.4
BLEA 4	Stage 1 effluent	58.1	33.0	6.1
BLEA 5	Stage 2 effluent	68.6	33.0	9.9
BLEA 6	Stage 3 effluent	68.2	33.0	2.8
BLEA 7	Stage 4 effluent	66.8	33.0	1.3
BLEA 8	Stage 5 effluent	73.1	33.0	6.0
BLEA 9	Prewasher-effluent	49.4	33.0	1.5
DRY 5	Drying - effluents	62.1	33.0	4.5
BLC 10	Steam condensation Cond. 3	62.2	61.2	32.7
BLC 11	Flash steam to train pre-evap	80.3	79.2	2.6
BLC 12	Flash steam to train pre-evap	72.9	69.3	1.6
BLC 13	Steam condensation Cond. 2	60.1	59.5	11.0
BLC 14	Steam condensation Cond. 1	75.9	74.9	12.3
BLC 15	CC- effluent	71.9	33.0	9.1
BLC 16	CC- effluent	79.2	33.0	9.6
BLC 17	Flash steam evaporators	113.1	113.0	8.2
BLC 18	Flash steam from stripper	110.0	89.0	10.2
DEA 3	Condensate mixed with water (NIM)	115.5	57.1	7.5
DEA 4	Flash steam to deareation (NIM)	143.3	137.7	1.7
BOIL 1	Flue gas from RB 1	164.0	105.8	4.3
BOIL 2	Flue gas from RB 2	199.0	117.6	4.6
BOIL 3	Flue gas from BB	182.0	126.5	2.9
BOIL 4	Boilers- blow down	235	33.0	2.1

Table 6-A3. Water sinks

Stream ID	Description	Flow t/h	Max. DSC allowed ppm
DRY 6	Drying - whitewater tank (62 °C)	6	6043
BLEA 15	Stage 1 requirement (71 °C)	200	2072
BLEA 17	Stage 3 requirement (71 °C)	191	1643
BLEA 18	Stage 2 requirement (71 °C)	199	1557
WASH 1	Washing (71 ℃ and 58 ℃)	406	1240
DRY 7	Drying – separator (62 °C)	39	965
BLEA 19	Stage 5 requirement (71 °C)	189	693
BLEA 20	Pre-washer requirement (58°C)	228	0
BLEA 21	Gas Washer	1	0
BLEA 22	ClO₂ preparation	129	0
BLEA 23	NaClO ₃ preparation	10	0
DEA 5	Deareator	139	0
REC 1	Reacaustification (44°C)	59	0
DRY 8	Drying requirement (62°C)	216	0
BLEA 24	NaOH preparation	16	0
WP12	Vacuum Pumps	69	0
BLEA 25	Stage 4 requirement (71 °C)	190	0
BLEA 26	Static mixers	19	0
WP 13	Water by passed (clarification)	134	0

Table 6-A4. Water sources

Stream ID	Description	Flow	DSC
Stream ID	Description	t/h	ppm
BLEA 5	Stage 2 effluent	241	6125
BLEA 6	Stage 3 effluent	68	4137
BLEA 4	Stage 1 effluent	212	4036
BLEA 7	Stage 5 effluent	130	3428
BLEA 10	Water (71 °C) +Stage 3 filtrate	200	2072
BLEA 9	Pre-washer - effluent	78	1952
BLEA 8	Stage 4 effluent	34	1775
BLEA 11	Water (71 °C) + Stage 4 filtrate	191	1643
BLEA 12	Effluent separator	26	1618
BLEA 13	Water (71 °C) + Stage 5 filtrate	199	1558
WASH 2	Water (71 °C) + filtrate pre-wash	388	842
DRY 5	Drying - effluents	337	641
DEL 7	CC - effluent	19	0
BLC 19	CC - effluent	171	0
BLC 20	CC - effluent	190	0
BOIL 4	Boilers- blow down	12	0
WP 10	Water by-pass (clarification)	134	0
WP 11	Vacuum pump sealings - effluent	69	0

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CHAPTER 6

SYSTEMS INTERACTIONS ANALYSIS FOR THE RETROFIT OF A TYPICAL KRAFT PROCESS

6.1 Introduction

The interactions between the utilities systems and the process must be identified to formulate technically feasible energy enhancing options. There are various techniques to improve the energy efficiency of a process; however, these techniques must be applied in an iterative procedure to cast light on their synergies and counter-actions.

There is broad range of techniques available to the engineer and that should be considered in a retrofit project to enhance the energy efficiency of an operating process. The two best known techniques and most often utilized are internal heat recovery by means of process to process heat exchange and water reutilization by the application of systems closure measures. The development of a heat recovery program aided by Pinch Analysis[®] is well documented (Linnhoff et al., 1994a). Similar approaches such as Water Pinch[®] are also available to assist in the development of a system closure program (Dhole, 1998). They are usually applied independently yet, the results generated by either of the techniques may restrict the options available to the other; to maximize the global benefit to the process, they should be applied in conjunction in an iterative manner.

There are other energy enhancing techniques, such as: the increment of the rate of condensate return to the utility system, the elimination of non isothermal mixing for heating or cooling and the adjustment of the temperature or pressure levels of the utilities. These techniques are often ignored in energy retrofit projects yet, they can have a significant effect on the overall steam consumption but they may also limit the scope of internal heat recovery and system closure. There are also vast amounts of heat at low potential in various process streams near ambient temperature, which cannot practically be recovered by the techniques mentioned above. Upgrading some of this heat to a useful level by means of a heat pump can, in some cases, yield significant energy gains. Absorption heat pumps can be attractive because of their specific

characteristics (Bakhtiari et al 2009). Finally the availability of excess steam production capacity generated by an energy integration project can be used to produce electric power for sale thus generating revenues to offset energy costs and investments.

All those possibilities must be evaluated and jointly implemented by a procedure which takes into account their interactions sometimes leading to synergies, sometimes to counter effects.

A method has been proposed to investigate and elucidate the interactions between the factors affecting the energy efficiency and their effect on process steam consumption. Several energy enhancing techniques are considered: internal heat recovery, water reutilization, elimination of non isothermal mixing, energy upgrading and conversion, and condensate recovery. Key performance indicators and an analysis of the thermal composite curves deviation are employed to monitor the variations of the energy balance following the application of each technique. As a result, several cases to improve the energy efficiency have been developed. The most advantageous results must be retained. The method has been applied to the case study. It has been found that the water reutilization is the core of the process improvement, as the energy balance is modified, thus affecting the measures to be proposed by the other techniques. The cases where water reutilization is taken into account result in more steam savings, and less surface of exchange required for internal heat recovery.

6.2Methodology

The enhancing techniques could be regrouped as shown in Table 6-1. Some techniques modify the thermal composite curves. The process systems or sections affected must be identified so as to define the appropriate sequence of analysis and improvement.

Table 6-1 Classification of the energy enhancing techniques

Do not change	Change
the thermal composite curves	the thermal composite curves
Internal heat recovery (IHR)	Water reutilization (WR)
Energy upgrading (EU)	Elimination of non isothermal mixing (NIM)
Energy conversion (EC)	
Condensate Recovery (CR)	

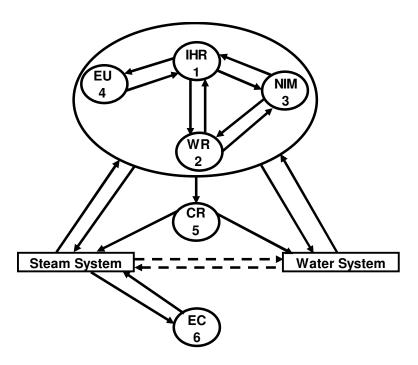


Figure 6-1 Interaction analysis procedure

Figure 6-1 represents the schematic of the systems interactions. The improvement of the internal heat recovery in the process is done by the implementation of a heat exchanger network (HEN). The configuration of the HEN depends on the thermal composite curves which are affected by the rate of water reutilization and the presence of non-isothermal mixing (NIM). The water reutilization measures save water and steam. These measures might involve NIM points which temperature should be taken into account to avoid using water sources colder than the fresh water previously used. NIM associated with a heat recovery penalty (pinch rules violation) should be identified. The elimination of NIM points can be done by changing the stream mixing arrangements and by internal heat recovery. Some NIM points might be eliminated after water reutilization. Energy upgrading employs the unused hot streams after maximizing internal heat recovery. However, the design of the HEN can be oriented so as to envisage the future implementation of a heat pump. The increase of the condensate recovery rate should be based on a process where steam savings by other means have been previously achieved. The implementation of energy conversion technologies such as turbines should be performed after steam savings have been maximized and the steam pressure levels adjusted so as to increase the power production potential. Depending on the turbine arrangement to be implemented the heat load of the deareator (steam system), as well as the water consumption of the process can be modified. These aspects may affect the configuration of the HEN and the elimination of NIM points.

To identify the interactions in the process a sequential approach is proposed (Figure 6-2). It involves six steps. For each step several cases are developed and assessed by means of performance indicators:

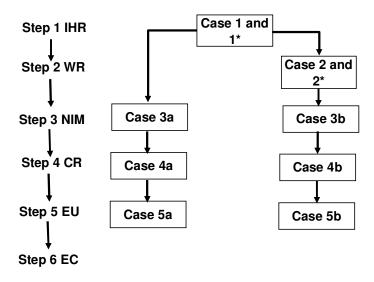


Figure 6-2 Interactions identification sequential approach

Step 1 Internal heat recovery: Development of a HEN (case 1) based on the current thermal composite curves and without taking into account other enhancing techniques. The effects of the technical constraints on the HEN are quantified (case 1*)

Step 2 Water reutilization: Identification of the water reduction measures effects on the thermal composite curves and on the development of the HEN (case 2). The effects of the technical constraints on the HEN are also quantified (case 2*)

Step 3. Elimination of NIM: Identification of inefficient NIM points in two perspectives; before (case 3a) and after (case 3b) water reutilization. The effects of eliminating NIM in the thermal composite curves for both cases are studied and the corresponding HENs developed.

Step 4. Energy upgrading: Re-design of HENs to fit the future implementation of absorption heat pumps (case 4a, 4b).

Step 5. Condensate recovery: After steam savings are maximized by the other techniques, the condensates that can be recovered are identified as well as the steam injections that can be replaced by heat exchangers (case 5a, 5b).

Step 6. Energy conversion: The implementation of cogeneration is proposed for the case with the maximum steam savings. The temperature profile is analyzed to optimize the pressure steam levels. The best arrangement of turbines is determined.

The effects of the interactions are assessed by the utilization of the key performance indicators used by Mateos-Espejel *et al* (2009c) for the benchmarking analysis:

- Steam and Water usage
- MER, MCR, PP (thermal pinch)
- Heat exchanger surface area
- Energy indicators: flue gases (EC_{FG}) and effluents (EC_E)

The energy content indicators and the steam savings are used to assess the efficiency of each step. The modification to the thermal composite curves illustrates the changes of the process requirements. The surface area of the HEN is used as an indicator of their cost. The computer simulation was used to determine the changes to the thermal and water balances resulting from the application of the enhancing techniques. Table 6-2 gives the steam savings achieved in each section and the overall savings for all cases. Table 6-3 presents other indicators for each case. The designs of the HEN have been obtained by means of conventional pinch design method (i.e. ASPEN-HXNET). The HEN for step 4 is presented because it represents an innovative contribution to the design aspects of a HEN.

Table 6-2 Steam savings by section

		Case									
Process Section	Current	-	*	2	2*	3a	3b	4a	4b	5a	2p
Delignification	32.4	0	0	0.7	0.7	0	0.7	0	7.0	0	0.7
Bleaching	14.2	0	0	1.6	1.6	0	1.6	0	1.6	0	1.6
Concentration	34.1	0	0	0.5	0.5	0	0.5	4.3	6.8	4.3	8.9
Drying	38.5	3.5	4	4	4	4	4	4	4	4	4
Water heating	12.9	5.4	12.1	12.9	12.2	12.8	12.9	8.6	9.5	9.8	9.5
Recaustification	4.6	0	0	0	0	0	0	0	0	0	0
Deareation	21.5	13.6	16.9	9.4	12.7	17.9	17.8	17.8	14.9	20.1	17.2
Steam export	5.6	0	0	0	0	0	0	0	0	0	0
Boilers, and other equip.	7.9	0	0	0.6	9.0	0	9.0	0	9.0	0	9.0
Total savings (MW)		22.5	33.1	29.7	32.3	34.7	38.1	34.7	38.1	37	40.4

Table 6-3 Indicators Assessment

		Case		Case	Case Case Case	Case Case	Case	Case	Case	Case	Case
	Current	1	1*	2	2*	3a	3b	4a	4b	5a	2p
MHR	122.8	122.8	122.8 119.1	119.1	119.1	122.4	118.9	122.4	118.9	122.4	118.9
MCR	10	10	10	17	17	7.3	15.9	7.3	15.9	7.3	15.9
Pinch point (°C)	1.1	71	1.1	25	25	71	25	71	25	71	25
Effluents energy content indicator, EC _E (MJ effluents											
/ MJ steam produced)	0.26	0.2	0.13	0.18	0.14	0.12	0.13	0.12	0.13	0.12	0.13
Flue gases energy content indicator, ECFG (MJ flue											
gases/ MJ steam produced)	0.07	0	0	0	0	0	0	0	0	0	0
Surface area needed (m2)		3580	6650	2120	6650 2120 3660	4641	2990	5860	5130	6080	5350

6.2.1 Step I: Internal heat recovery (IHR)

This step consists of maximizing the process to process heat exchanges through a HEN based on the current thermal composite curves (Figure 6-3).

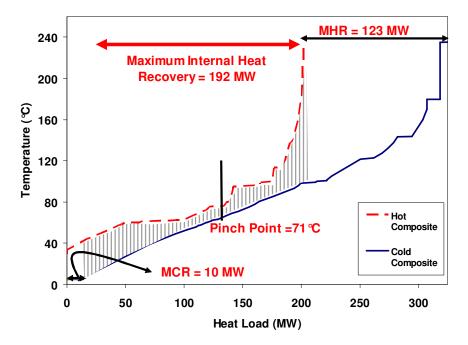


Figure 6-3 Thermal composite curves of the process in initial configuration

The development of the retrofit HEN must take into account:

- 1. Elimination of pinch violations
- 2. Utilization of currently unused hot streams (effluents and flue gases)
- 3. Identification of the heat recovery measures that affect the operation of the process

The existing internal heat recovery measures in the process were proposed to satisfy part of the water heating demand. However, the elimination of pinch violations and the utilization of available heat sources can increase the steam savings. Table 6-4 shows the amount of energy associated with the pinch violations as well as the utilization of steam above the pinch. There are three types of violations:

1. Utilization of a hot stream above the pinch point to heat a cold stream below it (12.5MW)

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

The difference between the steam used above the pinch and the minimum heating requirement (MHR) is the excess steam used above the pinch (26.8 MW). This excess is produced by the pinch violations 1 and 3. The elimination of the steam used below the pinch (22.2MW) and of the excess steam employed above it gives the maximum savings that can be achieved by improving internal heat recovery (49MW).

Table 6-4 Violations to the pinch rules in the current process (values in MW)

	Pin	ch violatio	ons		
Section	HXTP	UHAP	SUBP	SUAP	TSU
Delignification	5.3		0.9	31.5	32.4
Bleaching			2.1	12.2	14.3
Concentration				34.1	34.1
Drying			6.8	31.7	38.5
Water heating	1.7		9.8	3.1	12.9
Recaustification				4.6	4.6
Deareation	5.5	0.8	2.6	19	21.6
To sell				5.6	5.6
Boilers, & other		13.5		7.9	7.9
Total	12.5	14.3	22.2	149.7	171.9

Abbreviations: HXTP: heat transfer through the pinch; UHAP: unused heat sources above the pinch; SUBP: steam used below the pinch; SUAP; steam used above the pinch; TSU: total steam used

The internal heat recovery and heating arrangements that affect the operation of the process have been identified. They have been considered as technical constraints and have not been modified. These measures prevent reaching the MER and also avoid excessively complex and costly retrofitting HEN.

1. Heating fresh water by steam condensation in the BL concentration section. The vacuum used in the last effect of BL concentration is produced by an ejector coupled to the condensers. The associated heat exchange does not violate the pinch rules because both

streams are below the pinch point. However, these hot streams (steam condensation) could be matched with other cold streams below the pinch to increase the steam savings.

- 2. Heating contaminated water by direct injection of process steam. This direct heat transfer occurs in an accumulation tank used for process controllability. The tank is connected to the water system (heat exchanger after warm water tank in Figure 6-3) and the BL concentration section. Pinch violations account for 3.9 MW
- 3. *Delignification*. Medium pressure steam is used to increase the temperature in the digesters from 60°C to 170°C. The broad range of working temperature makes these equipments suitable for heat integration. However, modifying the configuration by implementing additional heat exchangers affect their controllability. Pinch violations account for 2.3 MW.
- 4. Live steam condensates directly returned to the deareator. The high temperature of these streams (~115°C) makes them suitable for heat exchange above the pinch point. However, they should not be used for this purpose because the heat requirement of the deareator would increase.

Two cases have been developed: Case 1 represents a HEN that includes all technical constraints while Case 1* encompasses a modification to the arrangement for heating fresh water by steam condensation (constraint 1). The objective of eliminating one of the constraints is to analyze the effects on the surface of the retrofit HEN.

The surface area and the complexity of the HEN increases as its energy requirements become closer to the MER. The design in Case 1 (savings = 22.5 MW) involves only the utilization of currently unused hot streams (bleaching effluents and flue gases). The reductions of steam used in water heating and in the deareator are the principal objectives of the HEN. On the other hand, for Case 1* a better usage of the available heat below the pinch represents more steam savings (33.1 MW). However, the surface required is doubled.

Steam savings measures above the pinch point recover the heat from the flue gases, which have high exergy content (Mateos-Espejel et al 2009c). An EC_{FG} value of zero shows that the available

heat from flue gases is recovered. The increased utilization of heat from effluents, below the pinch, in Case 1* results in a larger reduction of EC_E.

6.2.2 Step II: Water reutilization (WR)

The effects of increasing water reutilization on the process steam consumption as well as on the thermal composite curves and the retrofit HEN have been investigated in this step. Mateos–Espejel et al (2008b) have proposed reutilization measures based on Water Pinch and the analysis of the thermal composite curves:

- 1. Reutilization of the effluents from the BL concentration section, in the pulp washing and in the recaustification sections (savings =350 m³/h)
- 2. Reutilization of whitewater in the bleaching section (savings = 110 m³/h)
- 3. Increased reutilization of filtrate within the bleaching section (savings = 70 m³/h)
- 4. Reutilization of the sealing water of the vacuum pumps (savings = $70 \text{ m}^3/\text{h}$)

The implementation of these measures reduces the steam demand by 15.1 MW before enhanced IHR is considered. As could be expected the largest gains come from the reduction of the need for heating water (9.5 MW). Other significant gains are obtained in the deareator (2.3 MW) because less steam needs to be produced. The utilization of BL concentration section effluents (~75°C) to replace the hot water used for pulp washing (~70°C), increases the temperature of the washing filtrates recycled to delignification, and of the weak BL liquor (produced in the washing section) which is later concentrated. For that reason, the steam demand is reduced by 0.7 MW in delignification and by 0.5 MW in BL concentration. The same effect occurs in the pulp bleaching where the replacement of hot water by a hotter stream increases the temperature of the pulp thus eliminating steam injections accounting for 1.6 MW. Subsequently, the cold make up water and the heating needs of the deareator are reduced.

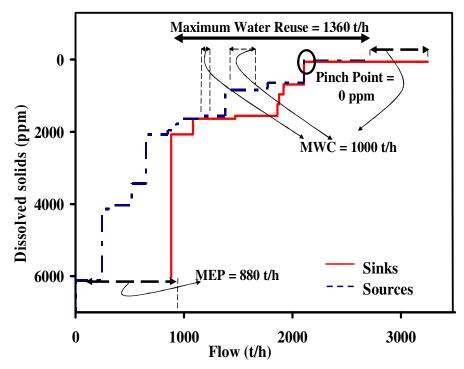


Figure 6-4 Water composite curves of the process

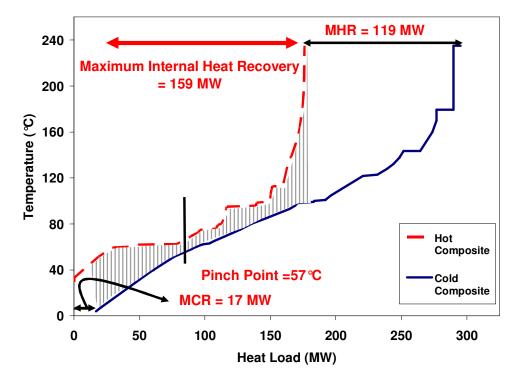


Figure 6-5 Thermal composite curves of the process after water reutilization

The water composite curves (Figure 6-4) are typically modified after internal heat recovery if the process uses cooling water. However, as this is not the applicable to the case study, these curves have remained unchanged during the interactions analysis.

After water reutilization, the process thermal composite curves have changed and new curves must be generated (Figure 6-5). The MHR is reduced by 3.7 MW while the MCR increases by 7 MW. The MCR changes because the production of hot water requirement is decreased. In consequence, part of the cold water used for steam condensation in the BL concentration section becomes an additional cooling demand for the overall process. A pinch violation is created in this heat exchange because the pinch point is reduced to 57°C. The violations to the pinch rules after water reutilization are shown in Table 6-5. The maximum savings that can be achieved by improving internal heat recovery are 37.4 MW.

Table 6-5 Violations to the pinch rules after water reutilization

	Pin	ch violati	ons		
Section	НХТР	UHAP	SUBP	SUAP	TSU
Delignification	3.5			31.7	31.7
Bleaching		4.9	.5	12.1	12.6
Concentration	5.5			33.6	33.6
Drying			2.5	36	38.5
Water heating	.09			3.4	3.4
Recaustification				4.6	4.6
Deareation	6.1	8.0		19.2	19.2
Steam export				5.6	5.6
Boilers, and other		13.5		7.3	7.3
Total	15.2	19.2	3	153.5	156.5

As in step 1, two retrofit HEN have been developed: Case 2 takes into account all technical constraints while Case 2* includes the modification of the arrangement for heating fresh water by steam condensation (constraint 1). The steam savings achieved by the water reduction measures (15.1 MW) have been included in the results of both cases. Case 2 saves 29.7 MW of steam that is more than Case 1 and less surface area is required. Case 2* produces more steam savings; however the exchange area needed is substantially larger.

The reduction of the EC_E is produced by effluents reutilization and increased heat recovery below the pinch. The required investment is lowered because less surface area for heat exchange is needed. In addition, the water reutilization measures involve only re-piping which is cheaper than new heat exchangers (Mateos-Espejel et al., 2008b).

6.2.3 Step III: Non isothermal mixing (NIM)

This step consists of identifying and eliminating the inefficient NIM points in the process. This operation modifies the thermal composite curves and subsequently the design of the HEN. NIM points are not usually given the appropriate importance when improving the thermal efficiency of a process (Brown *et al* 2005); yet, they may significantly influence the steam consumption. Savulescu and Alva-Argaez (2008) have proposed a methodology by which all NIM points and their thermal relevance are first determined. Then, the NIM-based paths (several NIM points connected) are identified and the temperature profiles evaluated. The final step is the analysis of the thermal efficiency of the NIM points, the related pinch violations and the redesign of the paths.

An analysis of the exergy destroyed associated with the heat transfer operations and which is an indicative of energy degradation has been done to identify the most inefficient NIM points. Two cases are represented in Figure 6-6: the process in its current configuration (Case 3a) and after water reutilization (Case 3b). For the Case 3a, the most inefficient NIM occurs in the deareator, in the condensate recovery system, in the accumulation tank and the hot and warm water tanks. The energy degraded at the hot and warm water tanks, after water reutilization, has been substantially reduced because no cold make up water (4°C) and no steam injections are required.

The direct heat transfer in the accumulation tank corresponds to the second constraint for the development of a HEN (step 1) and therefore this NIM point has not been eliminated. The hot and warm water tanks are part of the same NIM-based path (Figure 6-7a), as well as the deareator and condensate recovery (Figure 6-8a). Therefore, the focus of this analysis has been these two paths. As shown in Table 6-4 and Table 6-5, both sections contain pinch violations.

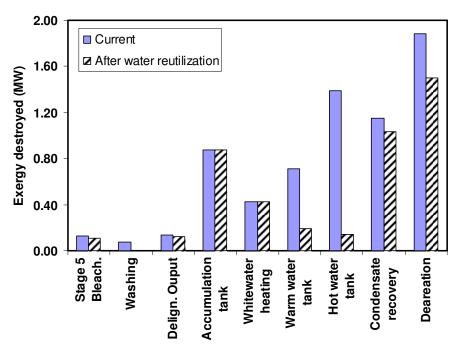


Figure 6-6 Exergy destroyed for different NIM points: current and after water reutilization configuration

Figure 6-7a shows the current hot water production path and Figure 6-7 b the modified path. It is proposed to preheat the cold water before the warm water tank to 59°C, with an available hot stream, and to segregate the stream at 62°C. These measures eliminate the need for direct injection of LP steam to the hot water tank and reduce the steam demand for heating water to 71°C. The appropriate hot stream is determined by the retrofit HEN. The temperature of the water is increased from 63°C to 68°C because less water is heated in the recovery heat exchangers, but the heat supplied is maintained. The temperature increase at the output of the hot water tank (2 °C) does not affect the performance of the process.

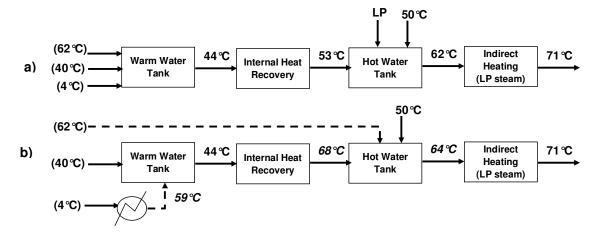


Figure 6-7 a) Current hot water production system; b) retrofit system

For the deareator, (Figure 6-8b), it is proposed to increase the temperature of the cold water to 137°C by internal heat recovery which substantially reduce the need for LP injection. The appropriate hot stream is determined by the retrofit HEN.

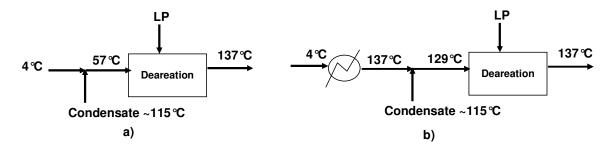


Figure 6-8 a) Current deareation system b) retrofit system

The modifications affect the temperature of some cold streams involved in the pinch analysis. In consequence, the MER and the design of the retrofit heat exchanger network should be recalculated. The new MHR and MCR, for Case 3a, are 122.4 MW and 7.3 MW respectively (Figure 6-9). The pinch violations corresponding to deareation and to water heating are eliminated. The HEN developed makes a better usage of the low temperature heat available in the process below the pinch point. This is illustrated in the large reduction of EC_E, from 0.26, in the current case, to 0.12 in Case 3a. The steam savings of 34.7 MW are largely superior to those obtained in Case 1. The reduction of the exergy destroyed in the warm water tank has a cascading effect reducing also the associated thermal inefficiencies downstream in the hot water tank and indirect heating.

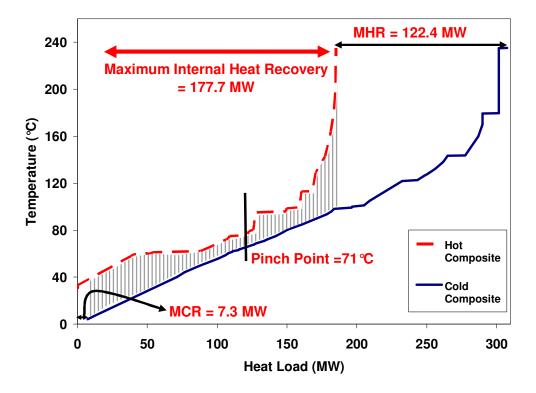


Figure 6-9 Thermal composite taking into account the elimination of NIM points (Case 3a)

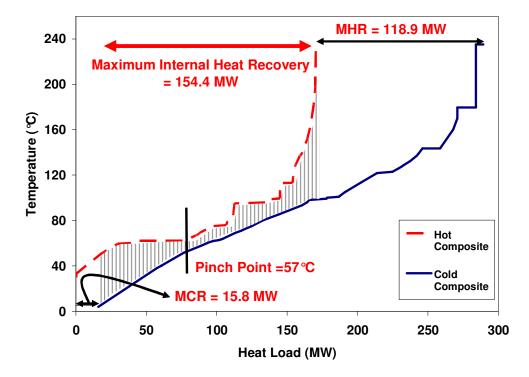


Figure 6-10 Thermal composite taking into account the elimination of NIM points (Case 3b)

For the water reutilization case, only the deareator path requires a modification. The new MHR and MCR are 118.9 MW and 15.9 MW respectively for Case 3b as shown in Figure 6-10. The developed HEN also makes a better usage of the low temperature energy below the pinch where EC_E is reduced to 0.13. The steam savings are increased by 8.4 MW but more surface exchange is required than in Case 2.

The improvement at the beginning of NIM-based paths has a cascading effect downstream, which shifts the energy demands from high (steam) to low temperature heat sources (effluents). Therefore, the steam savings achieved by internal heat recovery are increased.

6.2.4 Step IV: Energy upgrading

The object of this step is to re-design a HEN to make the implementation of absorption heat pumps (AHP) possible. AHP's are devices that can upgrade low temperature heat by exploiting the effect of pressure on an absorption–desorption cycle to accomplish the temperature lift needed for the heat pump effect (Costa et al., 2009). AHPs are environmentally friendly as they use benign working fluids which do not generate greenhouse effects. They are thermally driven and can be activated by waste heat. They can also be part of trigeneration systems where the AHP is driven by the steam discharged from a turbine (Marinova et al., 2007) resulting in a triple gain: hot and cold utility are saved and power is produced. This energy technology is an interesting measure to decrease even more the steam consumption after the process has been improved in terms of water reutilization and internal heat recovery.

The proper positioning of AHP's in a process must take into account the pinch point. The energy to be 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). The technical feasibility of an AHP depends on the target temperature of the cold stream and on the temperature lift required, which should be as small as possible. As a result, the best option for implementing an AHP requires either the hot stream or heat receptor to be close to the pinch point.

In this step the HENs have been redesigned to leave the heat receptors close to the pinch free for the posterior implementation of AHPs. The HENs which have been re-designed are Case 3a and 3b. The new AHP compatible designs are represented by Case 4a and Case 4b.

The design of the HEN above the pinch point for Case 3b is shown in Figure 6-11. The utility heaters are used in the range of 100 to 137°C and the streams close to the pinch are used in process to process exchangers (HX 3 and 4). Considering that the pinch point after water reutilization is 57° C, the temperature lift required for a hot stream close to the pinch (i.e. bleaching effluents at 55° C) would be ~80°C. In order to implement an AHP (Figure 6-12), the hot streams above the pinch should satisfy the energy requirement of the high temperature cold streams (100 to 137° C) as performed by HX B and D in Case 4b. The heat receptors close to the pinch are available for the AHPs. However, the surface area required by the process to process heat exchangers is larger because their $\Delta T_{approach}$ decreases. Case 4a (before water reutilization) and Case 4b (after water reutilization), in Table 6-2, give the characteristics of the new designs. On the other hand, these options become interesting when power production is also part of the process retrofit because the more steam is saved in the process, the more it can be used to produce power.

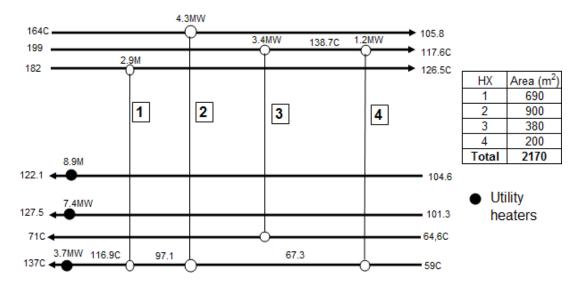


Figure 6-11 Case 3b: network design above the pinch

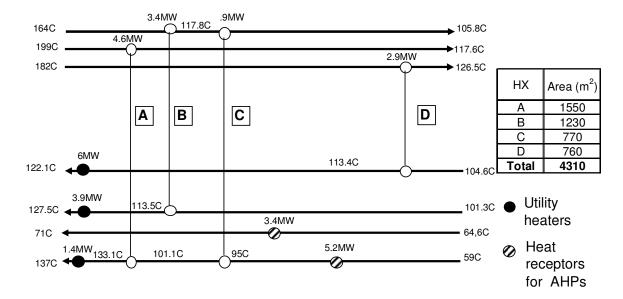


Figure 6-12 Case 4b: network design above the pinch

6.2.5 Step V: Condensate recovery (CR)

The condensate recovered in a mill reduces the steam required for deareation. This technique must be performed after steam savings have been achieved by the other means so as to identify the operations where condensate is still produced and whether it can be recovered. In addition, the direct steam injections that were not previously eliminated can be replaced by heat exchangers in order to increase the condensate return rate.

Two measures have been identified: replacement of steam injection used to heat whitewater by a heat exchanger and the collection of condensates produced in the recaustification unit. The results for Cases 5a and 5b (Table 6-2) diverge on two points from Cases 4a and 4b: the reduction of the steam consumption for deareation (2.3 MW) because less cold water is required and, the increase of the surface area.

6.2.6 Step VI: Energy conversion

The evaluation of energy conversion systems has to be done after the thermal optimization. The objective is to compute the proper size and type of turbines, required for the amount of steam available for power production.

Cakembergh-Mas et al (2009) studied the implementation of cogeneration for this case study. They considered condensing and backpressure turbines, and the related economic factors (turbines cost, price of electricity and of biomass). The potential replacement of the biomass boiler by a new one (twice the size and producing steam at VHP: 8800kPa) was also taken into account. Mateos-Espejel et al (2009a) adjusted the steam pressure levels to improve its match to the temperature profile of the process. In addition, the energy improvement of the process and the shutdown of the fossil fuel boiler were taken into account.

The implementation of two turbines is envisaged for the Case 5b: a backpressure 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. A maximum production of 44.4 MW is obtained.

6.3 Conclusions

The identification of the systems interactions is a fundamental step on the optimization of its energy efficiency. The interactions cause changes to the configuration and thermal balance of the process by the application of several enhancing techniques. Higher steam savings are obtained by this procedure than by tackling energy and water issues separately.

The elucidation of the changes to the thermal composite curves is a requisite for the development of a retrofit HEN. The absence of this consideration results in HENs that do not take advantage efficiently of the available energy sources of the process.

The utilization of the heat from the flue gases is the principal measure to save steam above the pinch point. Further steam savings are produced by a better use of the heat below the pinch point by water reutilization and elimination of NIM points. In addition, the investment required by the retrofit HEN is decreased. The re-design of HENs to integrate an AHP increases the surface area, but also the revenues obtained by the implementation of a cogeneration unit.

The enhancement measures derived by the interactions analysis are the basis of a strategy for improving the energy efficiency of the process. This strategy should take into account the technical and economic aspects of the implementation.

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CHAPTER 7

IMPLEMENTATION STRATEGY TOWARDS AN ENERGY EFFICIENT **KRAFT MILL**

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Keywords: energy efficiency, Pinch analysis, Water Pinch, Cogeneration, Absorption heat

pumps, Kraft process

7.1 Presentation of the article

This paper has been submitted to the Applied Thermal Engineering Journal. A strategy for implementing the measures that result of the systems interactions analysis is presented. The strategy has 3 objectives: elimination of fossil fuel, liberation of steam capacity and production of power. Economical and technical constraints are considered. A post-benchmarking analysis is presented to evaluate the improvement of the energy efficiency after all measures have been implemented.

7.2 Abstract

A strategy for implementing energy enhancement programs must be based on the results of systems interactions analysis. The development of such a strategy must take into account the existing process configuration and operating conditions in the most advantageous way. It must also be situated in the context of the management strategic plan of the industry. Considering all these issues, an analysis has been applied to an operating Kraft pulping mill in Eastern Canada. As a result a three-phase strategy was developed, it consists of the elimination of fossil fuel, the liberation of steam and the production of power. The proposed measures tackle different aspects

of the energy efficiency in a chemical process: condensate recovery, water reutilization, internal heat recovery, elimination of non isothermal mixing points, implementation of absorption heat pumps for energy upgrading, and cogeneration of power. Technical constraints in the cases of heat recovery from flue gases, and water reutilization have been taken into account. The economic analysis shows that the first phase is attractive because of the high price of fossil fuel. The subsequent steam savings measures are important as they increase the potential for power production

7.3 Introduction

Improving the energy efficiency of its manufacturing processes has been for some time a major concern of the pulp and paper (P&P) industry. The concern is shared by most industries. Over the years, remarkable progresses have been accomplished. Energy efficiency enhancement can designate a great variety of potential actions that can be taken. They range from simple good practice measures to complex engineering projects; some produce large savings, others small incremental projects; some require large investments, others low cost process adjustments. Paris (2000a) has proposed a classification of energy enhancing techniques in three categories which should be implemented in succession: good housekeeping, process operation control and advanced energy optimization. First, measures concerning equipment maintenance, pipes isolations, leaks detection and corrections should be implemented; at this stage personnel training and awareness programs for continuous improvements should be put in place. In a second phase the emphasis should be put on detecting and correcting individual unit operations problems often related to inadequate control systems: excessive process variability, set-point shifts and poor performance. The final phase involve more complex measures that groups of units or even the whole process internal heat recovery, water reutilization, condensates return, effluents minimization and the incorporation of energy upgrading and conversion technologies. At this level of complexity, individual measures may affect each other, sometimes in synergy, sometimes with negative effects. These interactions must be identified early in the analysis and used to advantage. The analysis should be global, i.e. at the mill site scale, and encompass all phenomena that impact significantly upon the thermal energy consumption of the site. The conclusion of an

advanced optimization study should be the development of an implementation strategy which integrates economic criteria as well as thermal and technical constraints.

The P&P 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 is generated from biomass, the industry remains largely fossil fuel dependent. High water consumption which impacts directly upon its thermal energy consumption adds to its energy challenge (Turner, 1994). Overall, energy accounts for up to 30% of the total pulp manufacturing cost. In the context of high energy prices, more stringent environmental regulations, and fierce competition from emerging producing regions the industry has increased its R&D efforts towards energy efficiency technologies and water conservation alternatives. This paper presents an implementation strategy to increase the energy efficiency of an operating Kraft pulping mill in Eastern Canada. The measures proposed are derived from an interactions analysis of different energy enhancing techniques to improve the performance of the mill by Mateos-Espejel et al (2009c). The strategy can be implemented in a stepwise manner. The objective of the first phase is to eliminate the use of fossil fuel to produce steam. This phase is remarkably cost-effective because of the high cost of fossil fuel. The objective of the second phase is to liberate additional steam producing capacity to increase power generation potential. The energy efficiency measures proposed in this phase are much less attractive than those envisaged in the first phase when considered by themselves because they reduce the demand of low-cost steam produced by wood residues (bark, rejects from chips processing). However they open possibilities for the very profitable production of electricity for sale to the grid. The third phase, concerns the implementation of energy upgrading and conversion technologies such as, absorption heat pumps (AHP) and cogeneration. Those two technologies can be coupled by using the steam released by the turbines of a cogeneration plant to drive an AHP. This arrangement called trigeneration can be advantageous as it can simultaneously reduce the load on heating and cooling utilities and produce power for sale.

7.4 Context

The process analyzed in this work is an operating Kraft mill situated in Eastern Canada. An energy-oriented process simulation of the mill has been developed on the software CADSIM

Plus; it is based on nominal values of operation parameters. The energy performance of the mill has been benchmarked (Mateos-Espejel et al., 2009b). The mill has an average production of 700 adt/d (adt = air dried ton) of high grade bleached pulp.

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). 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, black liquor, separated from the fibers in the washing section, is concentrated and burnt in the recovery boilers 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 boilers. 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. A simplified schematic of the mill showing the principal process sections is given in Figure 7-1.

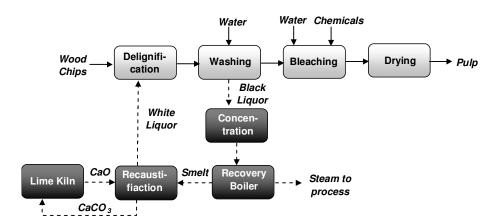


Figure 7-1 Simplified diagram of the Kraft process

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

The mill uses an 8 batch digester sequence for chemical delignification and a five stage bleaching sequence which uses different bleaching agents (ClO₂, H₂O₂, NaOH) at different conditions. The weak black liquor (BL) concentration (15% solids concentration) is performed in two steps; first, the BL is passed through a set of pre-evaporators (19% solids concentration) driven by recycled steam, and then it is sent to two parallel trains (55 % solids concentration) with post-concentrators (70% solids concentrators) driven by live steam. Drying is performed in two steps: first, the pulp passed through a set of cylinders (dominion dryer) where water is evaporated by indirect heating; and then hot air is used to attain the final specification of pulp consistency (flakt dryer). Additionally, steam is also exported to an adjacent sawmill.

The mill plans to replace the current aging biomass boiler by a new one (NBB) that will produce 140 t/h of very high pressure steam (VHP: 8825 kPa). One of the principal objectives of the NBB is to produce steam so as to produce power. This consideration has been considered in the last step of the strategy.

7.5 Previous work

The base-case process simulation of the mill contains detailed models of the steam and water utility systems. They have been described in Mateos-Espejel et al (2009d). A brief description of those two key systems is given below.

Steam system

To satisfy the steam demand of the mill (Figure 7-2), there are four boilers that generate high pressure steam (HP=3100 kPa, T = 371°C): two spent liquor recovery boilers, a biomass boiler and a small fossil fuel boiler. 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 (PRV). Part of the condensate produced in the process is recovered and mixed with make up water at the deareation stage. Table 7-1 gives the steam consumption for

each process section for winter conditions. The steam consumption is reduced by 10% during the summer.

Table 7-1 Steam consumption by process section

~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~	
Process section	GJ/adt
Delignification	3.99
Bleaching	1.75
Concentration	4.2
Drying	4.76
Water heating	1.54
Recaustification	0.57
Deareation	2.66
Steam exports	0.69
Boilers, and other equip.	0.98
Total process consumption	01 11

Total process consumption 21.14

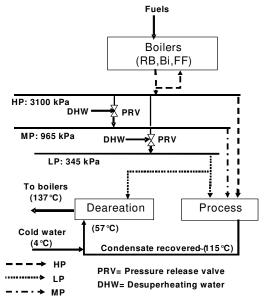


Figure 7-2 Steam Production

Water system

The water used in the process undergoes two pretreatments before being employed: During summer, the period of highest water consumption, 65 % of the feed 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, bleaching, ClO₂ preparation, and pulp drying. This water will be referred to as treated water. The remaining 35% is only screened and it is used for indirect cooling, steam scrubbing and house keeping: it is called screened water. Table 7-2 shows the water consumption of the process sections.

The treated water is used at 3 temperature levels (Figure 7-3): 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 concentration section. Hot water at 58°C is produced by indirect heat exchange with the concentration effluents. 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.

Table 7-2 Water consumption by process

section	
Process section	m³/adt
Treated water	
Delignification & Washing	10,1
Bleaching	30,7
Concentration	1,0
Drying	10,7
Recaustification	2,0
Deareation	4,8
To sell	0,0
Boilers	0,2
Non process uses	4,6
Screened water	
Bleaching	24
Recaustification	4,6
Non process uses	11,1
Unaccounted water	6.4
Total process consumption	110,1

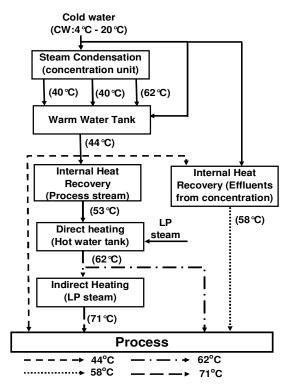


Figure 7-3 Water production

Pre-benchmarking Analysis

Mateos-Espejel *et al* (2009b) have performed a benchmarking analysis of the case study considering a three-pronged procedure: comparison with the current practice, targeting by means of the heat and water composite curves and the use of new performance indicators based on the exergy and energy contents of key energy sources. The exergy content encompasses the quantity and quality (temperature level) of the heat flows in, out and within the process. The following results were obtained:

- Water and steam consumption of the mill are above the typical Canadian averages.
- The process has a net thermal energy deficit of 8.1 GJ/adt which is defined by the amount of steam required by the process which cannot be supplied by the recovery boilers.

- The total flow of sewered effluents from pulp bleaching, drying, and BL concentration sections is above the typical Canadian average.
- The cooling demand of the process is 62 MW in winter and increases by 22 MW during the summer. A major contributor to the summer cooling demand is the water required by the bleaching agent making plant.
- A large fraction of the exergy supplied to the process (61%) is destroyed due to large temperature gradients in the boilers (HP steam production) and subsequent depressurization (MP and LP production).
- The unused heat content rejected to the environment by liquid effluents and flue gases represents 33% and 25% of the energy and exergy requirements respectively.
- The steam used for water heating represents 22% (37.1MW) of the total consumption by the process. About 33% of the exergy supplied (12.1 MW) to the water heating systems is destroyed.
- The thermal composite curves of the process are shown in Figure 7-4; the minimum heating requirement (MHR) is 123 MW, the minimum cooling requirement (MCR) is 10 MW and the pinch point is at 71°C.
- The water composite curves are shown in Figure 7-5. The minimum water consumption (MWC) is 1000 m³/h, the minimum effluent production (MEP) is 880 m³/h and the pinch point is at a dissolved solids concentration (DSC) of 0 ppm, that is for pure water.
- If the maximum internal heat recovery and water reutilization indicated by the composite curves were achieved (192 MW and 1360 t/h respectively), the steam consumption would decrease by 29% and the water consumption by 31%.

A post-benchmarking analysis is performed after the implementation of all measures to quantify the improvement in energy efficiency.

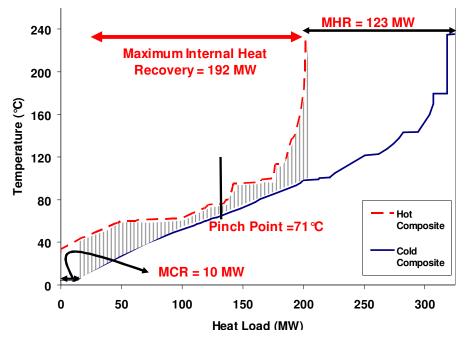


Figure 7-4 Thermal composite curves of the process

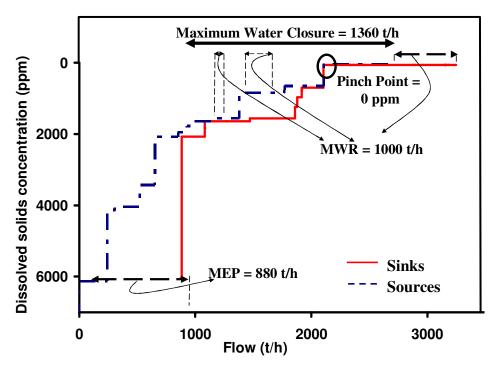


Figure 7-5 Water composite curves of the process

Interactions analysis

Mateos-Espejel, et al (2009c) have proposed a procedure to identify and quantify the interactions between the process systems by the application of several energy enhancing techniques. From this analysis the best options to improve the process were determined. Water reduction (WR) measures should be implemented prior to increasing internal heat recovery because they affect the overall thermal balance and they reduce the investments required for the subsequent retrofit heat exchanger network. After the implementation of these measues, the low temperature heat available below the pinch point is significantly reduced, and so does the water heating requirement below the pinch. Additionally, the MHR is decreased by 3.7 MW and the MCR is increased by 7 MW. The elimination of non isothermal mixing (NIM) points is taken into account to generate opportunities to use the available low temperature heat sources such as sewered effluents and save steam. Modifications to eliminate NIM points would further reduce both MHR and MCR by 0.2 MW and by 1.1 MW respectively. As a result the basis for improving internal heat recovery is a pinch diagram (Figure 7-6) with a pinch point of 57.7°C, a MHR of 118.9 MW and a MCR of 15.9 MW.

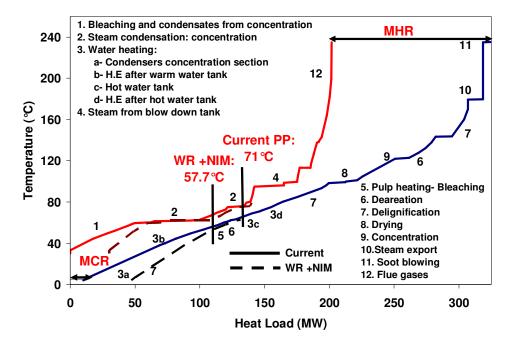


Figure 7-6 Thermal composite curves before and after WR and elimination of NIM

The implementation of absorption heat pumps (AHP) is done once the internal heat recovery is completed because process to process heat exchangers less expensive than AHP's should be preferred. However, AHP's can be attractive when integrated to a trigeneration unit (AHP + cogeneration) which produces a triple gain: savings of heating and cooling utilities and power production. The internal heat recovery measures have been developed so as to leave available the heat sinks above but close to the pinch point for potential use by the AHP. The strategy presented below is derived from this interactions analysis.

7.6 Implementation strategy

The optimal Kraft mill should produce enough steam from biomass fuels such as spent liquor and wood waste to supply its full energy requirement and still be able to produce power for sale to the grid (Browne et al., 2001). Yet, a typical Canadian mill may produce as much as 40% of its steam requirement from fossil fuels (Wising et al., 2006). Therefore, individual measures to reduce steam demand can be economically attractive (Dylke et al., 2003). However, the implementation of energy efficiency measures in a mill where a cogeneration unit is already installed can increase the operating costs because additional steam savings may reduce the power production capacity (Towers, 2005). To always maintain the cogeneration unit at near optimal operating conditions, it can be advantageous to have a small excess steam production capacity which is vented when not used. As the existing process configuration and operating conditions vary from mill to mill it is important to develop a strategy for the implementation of energy improvement programs in the most advantageous way. 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.

For this case study, a three-phase strategy is proposed (Figure 7-7):

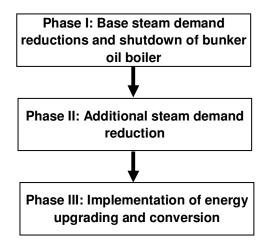


Figure 7-7 Implementation methodology

In the following sections, the energy enhancement measures constituting each phase are presented; their, thermal impact on the process, the potential savings and economic analysis are given. The simple pay back time (PBT) has been used as the economic indicator.

$$PBT = I / [(R + S) - OC]$$
 (1)

I = Investment; R = Revenues; S= Savings; OC = operational costs

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

- Direct and indirect expenses (i.e. material, labour, etc), CBM_{steel}=3.18; CBM_{Ti}=11.2
- Contingency and fee, CTM = 1.18*CBM
- Auxiliary facilities modifications (site development, off-site facilities, etc),
 CGR
 = 1.3 *CTM

All prices are in Canadian dollars and have been indexed to 2008. The cost of the steam 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 \$/m³ and the cost of effluent treatment 0.1 \$/m³ (Gullichsen and Fogelholm, 1999; Lovelady and El-Halwagi, 2007). The price of electricity sold to the grid is 90\$/MWh (Cakembergh-Mas et al., 2009b). The operating time of the mill is 8400 hours/a.

The process simulation on CADSIM PLUS has been used to design the energy enhancing measures proposed and to determine their impacts on water and steam consumption.

7.6.1 Phase I: Base steam demand reductions and shut down of the fossil fuel boiler

The maximum production capacity and the yearly average utilization of steam were computed from consumption data for several years (2002-2003 and 2005) made available by the mill (Table 7-3). The objective of phase I is to reduce the steam demand by 24.7 MW so that the fossil fuel boiler may be permanently shut down.

Table 7-3. Average and maximum utilization of steam

	Max	imum	Average		
Fuel used	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	

Live steam condensates Recovery System

The current condensate recovery rate is 46%. It is below the Canadian average of 75% and even below the average for old mills which is 60% (Bruce and Wilson, 1999). This low percentage may be caused by excess utilization of live steam injections or a by contamination of the condensate making it unusable as make-up water for the utility system. The proposed measures are identified by the interactions analysis once all possible steam reductions have been

maximized. However, these measures should be implemented first because they do not affect any part of the process other than the deareator. Two measures are proposed:

Measure 1: Recovery of clean condensate in recaustification section.

In the current process configuration, the clean condensates produced in the recaustification unit are directly sewered. The recovery of these condensates requires only the installation of pumps as the piping system is already in place.

Measure 2: Replacement of steam injection in the whitewater accumulator

In the current configuration (Figure 7-8a), the preheating of whitewater is achieved by direct steam injection. Whitewater is an aqueous suspension of particles of fibers entrained as water is drained from the pulp before drying. The replacement by a heat exchanger is proposed (Figure 7-8b).

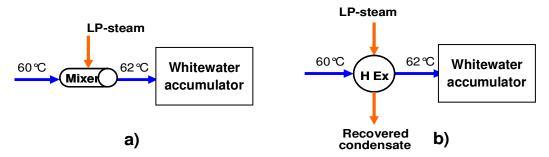


Figure 7-8. Whitewater preheating; a) Current; b) energy saving measure 2

These two measures are economically feasible and attractive, as the investments required are low and the pay back times very short (Table 7-4). The rate of condensate recovery increases to 57%. This improvement brings the mill on par with the other old Canadian mills but below the Canadian average.

Table 7-4 Economic analysis installation of a heat exchanger

	Steam Saved (MW)	Investment (M\$)	Savings (M\$/a)	P.B.T (a)
Measure 1	0.5	0.05	0.3	0.2
Measure 2	1.8	0.2	0.9	0.2
Cond. Rec.	2.3	0.25	1.2	0.2

Water Reutilization

The implementation of water usage reductions measures is the core of the process energy efficiency enhancement because they modify the energy balance of the mill. The cost of water reutilization measures is mostly associated with the installation of pumps, pipes and instrumentation.

The energy impacts of water utilization in the process have been determined by Mateos-Espejel et al (2008b). The water pinch method (Bedard et al., 2001; Dhole, 1998; Jacob et al., 2002; Paris, 2000a; Tripathi, 1996) was used to identify the proper water reduction measures by analysis of the sources and sinks composite curves. These curves were constructed in the mill benchmarking analysis done previously (Mateos-Espejel et al., 2009b) as presented in Figure 7-4. Thermal Pinch Analysis® (Linnhoff et al., 1994a) was used to study the thermal impacts of water reutilization from the changes caused in the composite curves and the minimum energy requirements.

The measures indentified involve the reutilization of several water sources:

- Condensates from the concentration section
- Whitewater
- Bleaching filtrates
- Vacuum pumps sealing water

Two types of measures have been identified: measures wherein water and steam are reduced (measures 3 and 4) and those wherein only water is saved without any major energy impacts (measures 5 and 6).

Measure 3: Reutilization of condensates from the black liquor concentration section

The condensates from the vaporized BL in the concentration section are unsuitable as make-up water for the deareator. They contain traces of contaminants which could hinder the efficiency of

the recovery boilers. The degree of contamination of those condensates increases as the BL progresses into the cascade of the multi-effect evaporators (Figure 7-10a). Also they contain methanol which could be transferred to the pulp (i.e. in the washing and bleaching plants) and cause pulp quality degradation. The most contaminated condensates, produced in the condenser of the last effect, are stripped with steam to remove part of the contaminants. Since their heat content is quite significant, they should be segregated and redirected to appropriate process units for reutilization (Figure 7-10b). In the current configuration of the process they are sewered after having been used to heat part of the mill fresh water intake.

The condensates from the 2nd to 6th effect of the BL concentration trains and the stripped condensate have a low methanol concentration and can be reused in the washing section and prewashing step of bleaching. The condensate from the 7th effect has a higher concentration of methanol but is suitable for reuse in the recaustification section.

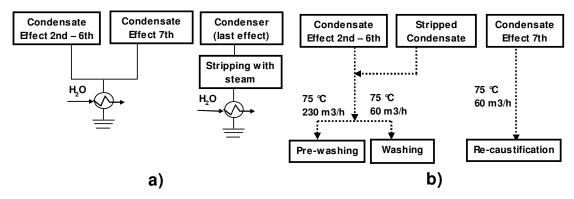


Figure 7-9. Condensates from BL section; a) Current b) Water reutilization measure 3

This measure saves 350 m³/h of water and 8 MW of steam. As the condensate temperature is higher than the temperature of the water currently used in the pre-washer, the temperature of the pulp also increases reducing the need of steam for pulp pre-hating between the bleaching stages. Similarly, the replacement of the water currently used for washing by condensates increases the temperature of the washing filtrates. This temperature increase reduces the steam consumption of the delignification and BL concentration sections where they are returned. This usage of the contaminated condensates has a number of cascading effects on the utilities systems:

• Elimination of make up water in the production of warm water

- Increase of warm water temperature
- Decrease consumption of steam for hot water production

Measure 4: Reuse of whitewater

Whitewater used in the washer of the last stage of bleaching is a common practice, and done in the mill; it can also be performed in the other stages (Towers and Turner, 1998). The measure proposed is to reuse whitewater, currently sewered (Figure 7-10a), in the washer of the second bleaching stage. This measure saves 110 m³/h of hot water and 4.2 MW of steam (Figure 7-10b). The steam is saved because less hot water at 71°C needs to be produced. The decrease of temperature at the input of stage 2 does not affect the performance in other part of the bleaching section nor does it increase the steam consumption.

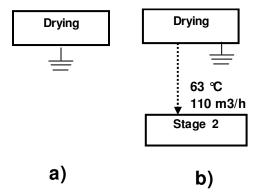


Figure 7-10. Reuse of white water; a) Current b) Water reutilization measure 4

Measure 5: Reuse of bleaching filtrates

Part of the bleaching filtrate from the stage 5 (180 m³/h) is currently reused in stage 3 (Figure 7-11). This can be increased by 15 m³/h without exceeding the DSC constraints on the washing stages. This measure reduces the water consumption and effluent production of the bleaching section. A further recirculation rate would violate the constraint.

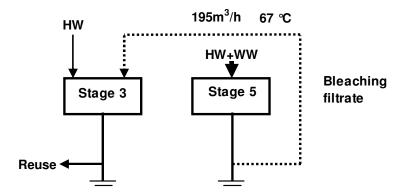


Figure 7-11. Bleaching filtrate reutilization; water reutilization measure 5

Measure 6: Vacuum pumps sealing water

In the current process configuration the vacuum pumps sealing water is sewered after usage. The temperature of the water, which must not be above 40°C to maintain vaccum, sets the limit for reutilisation of the water in the vacuum pump. It is possible to reuse up to 64 % of the sealing water effluent, without affecting the performance of the equipment (Houle et al., 1998). The implementation of this measure saves 70 m³/h of water (Figure 7-12).

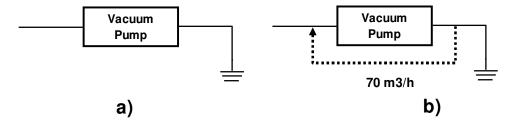


Figure 7-12 Vacuum pump sealing water; a) current b) Water reutilization measure 6

The water reutilization measures are very attractive due to the low PBT (0.2 a). After the implementation of measures 3 and 4, the utilization of steam for heating water is reduced by 77%. Also, steam is saved in the pulp bleaching, wood delignification and BL concentration sections. Additionally, as the steam requirement is diminished, the amount of fresh water and the steam used in the deareator (2.9MW) are also reduced. The low PBT (Table 7-5) of these measures is due to the associated steam savings. The PBT of measures 5 and 6 alone is relatively high because the price of water is much lower than that of steam. However, the implementation

does not imply any major changes in the process configuration, the investment required is low and the water savings are significant.

Table 7-5 Economic Analysis of Water Reutilization measures

	Steam Saved (MW)	Water Saved (m ³ /h)	Investment (M\$)	Savings (M\$/a)	P.B.T (a)
Measures 3 - 4	15.1	457	0.8	8.6	0.1
Measures 5 -6	0	84	0.6	0.1	5.3
Complete Water Reutilization	15.1	541	1.4	8.7	0.2

Internal heat recovery and non isothermal mixing points (NIM)

The available heat sources used in the internal heat recovery measures are the flue gases and the bleaching effluents (stages 1, 3 and 5 operate at acidic conditions while, stages 2 and 4 operate in alkaline conditions; Figure 7-6).

Measure 7: Fresh water pre-heating before deareator

This measure concerns the elimination of NIM points in the deareation system. In the current configuration, fresh water is mixed with the recovered condensates and sent directly to the deareator where live steam is injected to adjust the temperature (Figure 7-13a). This constitutes a pinch violation since steam is used below the pinch point, and a hot stream above the pinch is used to heat a cold stream below it. Therefore, it is proposed to increase the temperature of the water from 4°C to 133°C first by exchanging heat with the effluents from the pulp bleaching basic stages and then with the flue gases from the recovery boilers (Figure 7-13b). The steam savings come in part from fossil fuel (7.3 MW) and part from biomass (5.4MW). A possible heat sink to be utilized by an AHP has already been identified in a previous phase of the work (Mateos-Espejel et al., 2009c); however the installation of an AHP should only be done once all possible low temperature energy sources have been utilized for internal heat recovery, heat exchanges requiring a lower investment than AHPs.

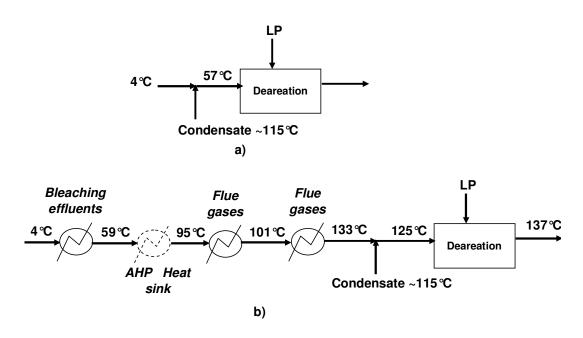


Figure 7-13 Fresh water pre-heating a) Current; b) Energy saving measure 7

The heat recovery from the flue gases requires a hot oil recirculation system, in which the oil is used as energy carrier from the flue gases to the process streams (Mostajeran-Goortani et al., 2009) as shown on Figure 7-14. The heat available from the flue gases is transferred in the heat recovery heat exchangers to the oil and distributed in the secondary heat exchangers to the cold streams. The allocation of the available heat to process streams is done in agreement to the Pinch Analysis[®] rules so that all target outlet temperatures of the heat sinks are met. Heat exchangers (HX) are made in titanium to avoid corrosion by the condensation of SO₃ contained in the flue gases and the secondary HX are made of stainless steel. The aggregate exchange surfaces for the recovery and secondary HX are 3460 m² and 870 m² respectively. The cost of the recovery HX is 7.1 M\$. The investment required for the secondary HX and tanks is of 3.2 M\$. The total heat available from the flue gases exceeds the requirement of measure 7. The balance will be used in measure 8 to reduce the steam consumption in the black liquor post-concentrator, which is part of phase II. The technical feasibility of this measure requires the installation of the hot oil loop system. The reason is that the circulating black liquor at 50 to 55% solids concentration to the flue stacks would require high pumping capacity and increase the difficulty to control the BL concentration section.

RBI RBII BB Recovery heat exchangers Hot Oil Tank Cold Oil Tank

Figure 7-14 Hot oil recirculation system

exchangers

The total investment required is of 10.3M\$, with savings of 3.2 M\$/a of biomass and fossil fuels and a PBT of 3.2 a. This relatively high PBT value by comparison to measures 1 to 6 is due to the low cost of biomass. However, measure 7 is necessary for the complete elimination of the fossil fuel requirement.

Economics of Phase I.

Measures:

Shutting down the fossil fuel boiler is a feasible and attractive option for the mill because the high price of this fuel makes the overall PBT (0.9a) of Phase I quite short.

Table 7-6 Phase I Economic Analysis

	Steam saved (MW)	Water savings (m3/h)	Investment (M\$)	Savings (M\$/a)	P.B.T. (a)
Measure 1-2	2.3		0.25	1.2	0.2
Measure 4-6	15.1	540	1.4	8.7	0.2
Measure 7 Phase I	12.7 30.1	540	10.3 11.95	3.2 13.1	3.2 0.9

The implementation of Phase I alone improves significantly the energy efficiency of the mill. Additional measures would save biomass, which is much less expensive than fossil fuel;

however, these options would liberate steam capacity for cogeneration and the extra generation of revenues for the mill.

7.6.2 Phase II. Additional steam demand reductions.

The measures proposed in Phase II include the rest of the internal heat recovery measures.

Measure 8: Whitewater reheating

Reheating whitewater as currently done (Figure 7-15a) is a pinch violation because live steam is used to heat a cold stream below the pinch point. The effluents from the pulp bleaching acidic stages can be used as heat source (Figure 7-15b). It requires a heat exchanger of 450 m². The material is titanium to avoid corrosion by the acidic effluents. The steam savings are 4.1 MW (0.2 M\$/a), with an investment of 1 M\$ and a PBT of 5 a.

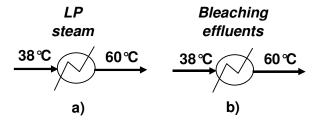


Figure 7-15 Whitewater reheating; a) Current; b) Energy saving measure 8

Measure 9: Black liquor post-concentrators

The post-concentrators driven by live steam at the end of each BL concentration train are the target of this measure. The remaining heat available from the hot oil recirculation system is used (Figure 7-16). The steam savings account for 6.3 MW. The investment required has already been counted with measure 7. The savings are 0.3M\$/a.

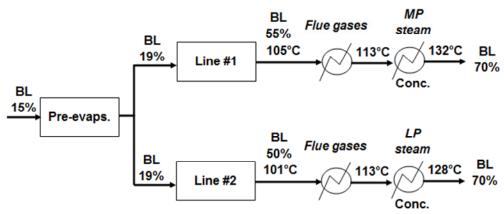


Figure 7-16 BL concentration section

Economics of Phase II.

Phase II is a prerequisite to increase cogeneration capacity, it is fully justified as will be shown in Phase III. The PBT is higher than in Phase I because of the low revenues (Table 7-7). However, as the price of biomass is likely to rise due to an increase demand for biofuels and other bioproducts, the PBT will decrease.

Table 7-7 Phase II Economic Analysis

	Steam saved (MW)	Investment (M\$)	Savings (M\$/a)	P.B.T. (a)
Measure 8	4.1	1	.2	5
Measure 9	6.3	-	.3	0
Total	10.4	1	.5	2

7.6.3 Phase III. Energy upgrading and conversion

The last phase of the strategy consists of integrating energy upgrading and conversion devices in the process in a way which maximizes the net benefit. To obtain additional savings after internal heat recovery has been accomplished, it is possible to upgrade low temperature energy sources by means of heat pumps. In this work, absorption heat pumps (AHP) have been considered. The AHP's can upgrade low temperature heat by exploiting the effect of pressure on an absorption–desorption cycle to accomplish the temperature lift from the heat source to the heat sink (Costa et

al., 2009). The low temperature heat source to be upgraded must be below the pinch point, while the high temperature heat source and the heat sink must be above it (Bakhtiari et al., 2007).

Energy conversion consists of transforming one type of energy into other of better quality or more useful. For instance, thermal energy can be converted into power, by cogeneration, to generate additional revenues. Cogeneration requires the appropriate installation of turbines to drive electric generators.

Cogeneration units and AHP driven by the steam discharge from the turbine can be combined in trigeneration units. The implementation of such units represents a triple gain to the process: heating and cooling loads are reduced, and power is produced. The implementation of trigeneration involves a two step procedure (Marinova et al., 2007): first, the AHP has to be optimally positioned in the process using the thermal composite curves and then cogeneration is implemented. In the following sections these two steps are summarized.

Measure 10 and 11: AHP implementation

(Bakhtiari et al., 2009) have made an analysis of the mill to determine the feasibility of installing AHPs. They have proposed to place an AHP in the chemical making plant. During the summer, refrigeration is needed in this section to produce chilled water at 6°C. For that purpose a vapor compression heat pump driven by electrical power and one ejector driven by MP steam are currently used (Figure 7-17). The proposition is to replace both heat pumps by only one double lift, MP steam driven AHP (Figure 7-18a), eliminating the utilization of electrical power. Additionally, the AHP upgrades the low temperature energy to reduce the steam demand of the process by 3.6 MW and the consumption of screened water by 540 m³/h. The units where steam is saved are the deareator, hot water production and whitewater heating. Figure 7-18a is a simplified schematic of an AHP where the heat sinks and sources are shown indicating only their current and target temperatures. Another single lift MP steam driven AHP (Figure 7-18b) has been proposed to upgrade the low temperature energy of the effluents from the pulp bleaching section. This AHP reduces the heating demand by 2MW. The units where steam is saved are the BL concentration and the deareator. The two heat sinks associated with the deareator, in both AHP's, have been previously identified in Measure 7.

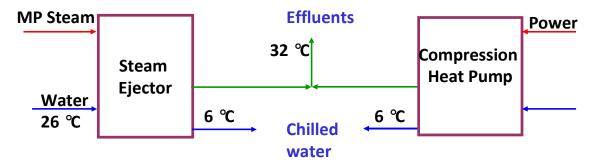


Figure 7-17 Current configuration for chilled water production

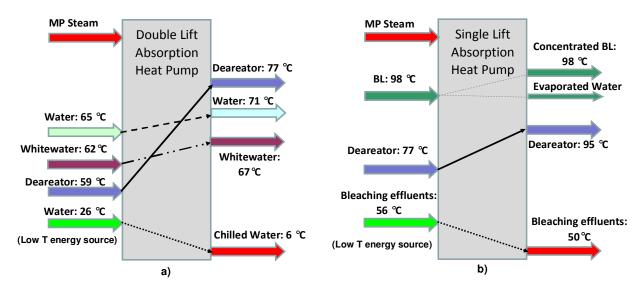


Figure 7-18 a) Double lift AHP for chilling water production in the chemical making plant b) Single lift AHP to upgrade the bleaching effluents heat content

Table 7-8 AHP economic analysis

	Steam saved (MW)	Water savings (m ³ /h)	Investment (M\$)	Savings (M\$/a)	P.B.T. (a)
Chemical Prod.	3.6	540	2.5	.4	7
Bleach. Eff.	2		1.8	.2	10
Total	5.6	540	4.3	.6	7

The implementation of the AHP's is expensive and with a long PBT (Table 7-8) because biomass is, for the time being, a very inexpensive fuel. The AHP for ClO₂ production is necessary to improve the operation of this part of the mill, and its correct positioning generates additional

revenues. In the case of upgrading the heat of bleaching effluents, the main objective is to reduce energy consumption for increasing power production.

Cogeneration

The installation of cogeneration is performed once all steam savings have been achieved, and the energy requirements of the AHP determined. In order to increase the power production potential, the pressure steam levels in the steam distribution network should be optimized. In the current process configuration PRV's and desuperheating are used to obtain the steam pressure distribution levels. This arrangement is inefficient as potential for producing power is lost in the adiabatic expansion.

The proposed cogeneration system has been developed in order to generate the maximum power production. One study have been performed prior to this work. Cakembergh-Mas *et al* (2009a) developed a MILP model to optimize the profitability of the power plant of the mill and they analyzed different scenarios of steam consumption and electricity prices.

Measure 12. Optimization of steam pressure levels

Mateos-Espejel *et al* (2009a)optimized the current steam pressure levels to increase the power production potential in the context of an energy efficient process. They determined the optimum steam delivery pressure by means of the grand composite curve (Figure 7-19) and showed that the current LP (345 kPa) can be reduced to 220 kPa. In addition, HP steam used in the pulp drying section can be replaced by MP steam, and the MP steam used in BL concentration section can be replaced by LP steam. These changes represent 10% of the power production potential.

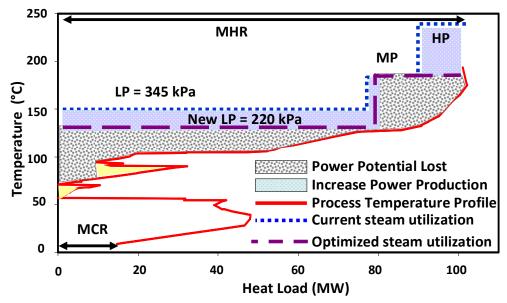


Figure 7-19 Grand composite curve and steam pressure levels

Measure 13. Implementation of two turbines

Taking into account the installation of the new biomass boiler, Cakembergh-Mas *et al* (2009a) proposed the implementation of two turbines (Figure 7-20): one backpressure (BPST) and one condensing (CST). Part of the MP produced by the BPST is used as the driving energy of the two proposed AHP's. The global configuration has a maximum power production of 44.4 MW during the summer and a minimum of 40.8 MW during winter.

The operating cost of cogeneration (16.1 M\$/a) is the cost of steam produced from biomass and used by the CST. The investment required for both turbines is 14.4 M\$, generating revenues of 33.7 M\$/a by sales of electricity to the grid. The low PBT (.8 a) makes this measure very attractive. The buyer's constraint for the sale of electricity is a minimum of 35 MW. This target can be surpassed in all seasons by the implementation of the proposed equipment.

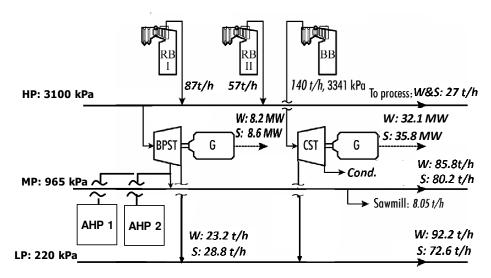


Figure 7-20 Cogeneration system to be implemented

Economics of Phase III.

The implementation of trigeneration brings additional benefits to the process. The proposed system is attractive due to the low PBT (Table 7-9), and its technical feasibility.

Table 7-9 Phase III Economic Analysis

	Steam saved (MW)	Water savings (m³/h)	Power produced (MW)	Investment (M\$)	Savings & revenues (M\$/a)	OC (M\$/a)	P.B.T. (a)
Measures 10 -11	5.6	540	-	4.3	.6	-	7
Measures 12 -13	-		44.4	14.4	33.7	16.1	.8
EUC	5.6		44.4	18.7	34.3	16.1	1

EUC = Energy upgrading and conversion; OC = Operating costs

7.7 Post-benchmarking

A post-benchmarking analysis should be done to quantify the improvement in energy efficiency of the current process. The changes of the indicators used for benchmarking is given in Table 7-10. 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 of energy as steam; this is less than the typical Canadian Kraft mill average of 18.5 GJ/ adt. The net thermal deficit will decrease from 8.1GJ/adt to 2.5 GJ/adt.

The mill reduces considerably its reliance on purchased fuel. The water savings will be $1080 \text{ m}^3/\text{h}$ (37.02 m³/adt) and the mill water consumption should be $73.1 \text{ m}^3/\text{adt}$, just below the Canadian average of $75 \text{ m}^3/\text{adt}$.

The effluents (EC_E), flue gases (EC_{FG}) and water heating indicators are used to estimate the amount of heat rejected to the environment. The energy content of the effluents is reduced from 0.26 to 0.11 (GJ effluents/ GJ steam produced). This is achieved by reducing the production of effluents and, by recovering their energy content by heat exchangers and heat upgrading. There is a substantial reduction of steam for water heating due to water reutilization and internal heat recovery. The energy content of the flue gases is recovered by internal heat recovery and it is used by the cold streams above the pinch point.

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.

Table 7-10 Postbenchmarking: indicators variation

Indicator	Current	Enhanced	⊿%	Reference
Current steam consumption (GJ/adt)	21.1	15.5	26.6	18.5
Water consumption (m ³ /adt)	110.1	73.1	33.6	75
Net thermal deficit (GJ/adt)	8.1	2.5	69.1	2.4
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

7.8 Economics of the complete implementation

The overall implementation with a PBT of one year is economically attractive at the current price of energy (Table 7-11). Further increases in the price of biomass and of electrical power and, the probable creation of carbon credits could further reduce the PBT very significantly.

Water Saved Power Investment **Profits** P.B.T. Steam saved (m^3/h) (MW) (MW) (M\$)(M\$/a)(a) 540 11.95 13.1 0.9 30.1 10.4 1 0.5 2

18.7

31.6

18.2*

31.8

1

1

Table 7-11 Economics of the full implementation strategy

44.4

44.4

5.6

46.1

540

1080

7.9 Conclusions

Phase I

Phase III

Total

The proposed strategy takes into account the technical and thermal constraints that affect the energy efficiency. The three main objectives have been accomplished: shutdown of the fossil fuel boiler, liberating steam capacity for power production and the implementation of a trigeneration system. The analysis of the systems interactions is fundamental to achieve these objectives. The recovery of heat from effluents and flue gases should be the priority for improving the energy efficiency of the mill. In addition, an energy efficient process should reduce to a minimum the usage of steam for water heating. The implementation of trigeneration generates additional revenues by the sale of electricity.

The energy efficient process will be eco-friendly since it will not use fossil fuels (except for the lime kiln), it will export steam and generate electricity. Systematic energy optimization with the application of advanced technologies, such as the one proposed, to improve the energy efficiency of processes in a cost effective way should become a standard procedure in the pulp and paper industry.

7.10 Acknowledgements

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^{*}Profits = revenues – operating cost

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CHAPTER 8

UNIFIED METHODOLOGY FOR THERMAL ENERGY EFFICIENCY IMPROVEMENT: APPLICATION TO KRAFT PROCESS

8.1 Introduction

The overall unified methodology that has been developed in this thesis is presented in this chapter. It identifies the complex interactions existing between the utilities systems and the process, as well as their impacts on the implementation of energy efficiency measures. This methodology incorporates energy, water and exergy aspects to evaluate and improve the process.

The definition and characterization, and the benchmarking analysis of the process base-case are done with steam and water perspectives. Several energy enhancing techniques have been used and their effects on the process systems identified. An implementation strategy that takes into account technical and economic constraint is the end result.

8.2 Unified methodology

The onion diagram commonly used in process design (Smith, 1995) has been modified to fit the unified methodology. This methodology has two principal objectives:

- The appropriate definition and analysis of the base case
- The improvement of the energy efficiency of the process taking into account several energy enhancing techniques, the interactions of the utility and process systems and, the economic and technical constraints

The methodology consists of four stages as shown in Figure 8-1. 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 benchmarking analysis. The base case is evaluated by a

comparison of its efficiency to the current practice of the industry and by the application of new 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 applied in an iterative procedure to cast light on their synergies and counter-actions Figure 8-2. The most advantageous results are 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. A detailed diagram of the unified methodology, indicating the steps contained in each stage, is shown in Figure 8-3.

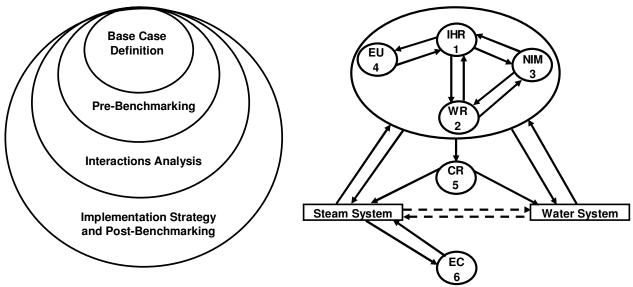


Figure 8-1. Unified methodology

Figure 8-2 Interactions analysis procedure

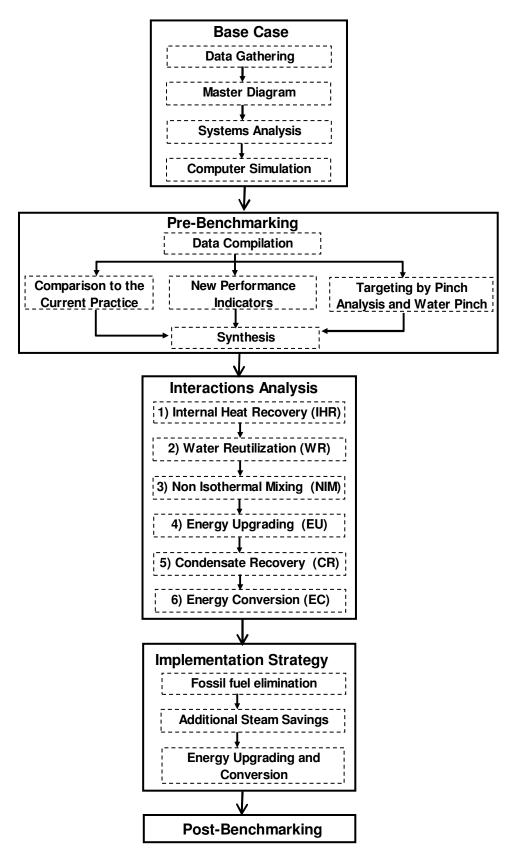


Figure 8-3 Detailed Unified Methodology

8.2.1 Stage 1. Base case

The development of a focused, reliable and representative model of an operating process is a prerequisite to the optimization and fine tuning of its energy performance. This model that will be referred as base case represents the current steady state of all process units. A four-pronged procedure (Figure 8-3) is used to define the base case nominal conditions: data gathering, elaboration of a master diagram, systems analysis, and simulation.

Data gathering

The data to be collected should represent the thermal and water performance of the process over a long period of time (i.e., steam and water consumption for one year). The sources for this information are the data acquisition systems, archieved values or process and instrumentation diagrams (PID). 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 PID's. 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

Water and steam are the driving forces of the material transformations that occur in the process. Therefore, both utility systems are defined in detail. Water-energy related subjects should also be analyzed: the various fuels utilization to produce steam, direct or indirect heating, the percentage of condensate recovery, and the water temperature levels.

Computer simulation

The complete process is simulated in a water-energy oriented perspective to study the interactions between the different systems and evaluate potential energy enhancing measures. The starting points for the simulation flowsheet 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.

8.2.2 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. The procedure will assist in the identification of:

- Unit operation with poor performance
- Maximum water reutilization and energy recovery theoretically possible
- Efficiency of the energy production and utilization

The pre-benchmarking procedure has 5 steps (Figure 8-3): data compilation, comparison to the current practice, additional performance indicators, targeting by Pinch Analysis and Water Pinch, and finally the synthesis of results.

Data Compilation

This step consists of gathering all data necessary to perform pre-benchmarking and to support the advanced steam and water analyses. It 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 in water analysis.

For the thermal analysis, the required heat load and delivery temperature of the corresponding steams are defined. The steam utilization units and the streams involved in internal heat recovery measures are identified. The streams involved in non isothermal mixing (NIM) points, including the direct injections of steam are identified at this step. This approach ensures that of all streams affecting the thermal behaviour of the process are taken into account.

For the water analysis, all fresh water utilization units and the streams involved in water reutilization are identified. It is important to determine the contaminants that affect the operation of the process or quality of the product. The maximum contaminant concentration allowed by the water-based operations is the nominal concentration obtained by analyzing the operation of the process as recommended by Foo et al (2006).

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 of this purpose. For instance, the steam or water consumption, of the overall process or a specific section, is 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

New performance indicators that encompass process variables that reflect the thermal inefficiencies of the process are used. These variables are the energy and exergy content of effluents, and flue gases. Exergy content is analyzed because it is a measure of quality and quantity of the energy produced and used by the process. Sankey diagrams of the exergy balances are constructed to identify 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.

Energy indicators. The energy content of effluents and flue gases represents the excess steam utilization by the process. The more energy rejected in these heat sources the more hot utility will

have to be supplied to the process. Two indicators that relate the energy content of effluents (EC_E) and flue gases (EC_{FG}) to the steam produced by the boilers currently operative in the process are defined. Another indicator that relates the total energy requirement for water heating (EC_{Wtot}) is also used.

Exergy indicators. 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 associated with heat transfer in the heat exchangers and the adiabatic expansion of a vapour in a valve. The exergy lost, is the exergy which is no longer useful or available for the process. It is associated with vented or sewered streams, the flue gases or heat losses to the environment. For the purpose of this work, only the exergy associated with the heat exchanges is considered. The exergy content of a heat flow is defined as the heat load (Q) multiplied by the Carnot coefficient (η). Internal heat recovery, effluents reutilization, cogeneration or heat upgrading are measures that reduce exergy losses and destruction. The exergy destroyed represents the lost potential for energy conversion (i.e power production). Thus an indicator (Exec) relating the exergy destroyed to the total exergy supplied to the process is defined. Exergy indicators are a ratio between the exergy content of hot effluents (ExCe) and flue gases (ExCe) and the exergy used by the process (Exproc). The addition of ExCe and ExCe represent a measure of the potential steam savings that can be achieved by internal heat recovery (ExCT). Another indicator that relates the exergy used for water heating (ExCwTot) is also defined.

The targeting by Pinch Analysis® and Water Pinch

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.

Synthesis

The main results are analyzed to evaluate the process. The causes of the inefficiencies and the limits of the possible improvement are established. Remarks on the interactions between the utility systems and the process are mentioned.

8.2.3 Stage 3. Interactions analysis

This stage consists of applying several energy enhancing techniques. Their impact on the process systems and their interactions are identified and analyzed. The objective is to develop a path for improving the process so as to maximize steam savings while minimizing the investment required. The enhancing techniques are regrouped, as shown in Table 8-1, according to whether or not they modify the temperature profile of the process. The systems or process section affected are identified so as to define the appropriate sequence of analysis and improvement.

Table 8-1 Enhancing techniques employed

Do not modify the temperature profile	Modify the temperature profile				
Internal heat recovery (IHR)	Water reutilization (WR)				
Energy upgrading (EU)	Elimination of non isothermal mixing (NIM)				
Energy conversion (EC)					
Condensate Recovery (CR)					

The interactions between the energy enhancing techniques are shown in Figure 8-2. The improvement of the internal heat recovery (IHR) in the process is done by the implementation of a heat exchanger network (HEN). The configuration of the HEN depends on the thermal composite curves which vary with the rate of water reutilization and elimination of non-isothermal mixing (NIM). Water reutilization (WR) measures save water and steam. The elimination of NIMs points can be done by changing stream mixing arrangements or by internal heat recovery. NIM points should be eliminated after water reutilization has been implemented. Energy upgrading (EU) makes up the heat sources still available after internal heat recovery has been maximized. However, the design of the HEN can be re-oriented so as to create opportunities for the integration of heat pumps. The increase of the condensate recovery (CR) rate should be based on a process where steam savings by other means have already been achieved. The implementation of energy conversion (EC) technologies such as turbines should be performed after steam savings have been maximized to increase the power production potential.

A six-step sequential approach is used to evaluate the energy enhancing techniques and the interactions between the process systems for improving the global thermal energy efficiency (Figure 8-3). The modifications to the temperature profile are identified by analyzing modifications to the thermal composite curves. These modifications produce different retrofit HEN options. The surface area of each HEN is used as an indicator of cost and complexity. The energy content indicators and the steam savings are also used to assess the efficiency of each step. The simulation was used to quantify the changes to the thermal and water balances produced by the enhancing techniques. The energy upgrading is performed by absorption heat pumps (AHP).

For each step of the procedure several cases are developed and the indicators assessment is performed:

Step 1 Internal heat recovery. Development of a HEN based on the current process temperature profile and without taking into account other enhancing techniques. Violations to the pinch rules are also determined.

Step 2 Water reutilization. Identification of the effects of water reduction measures on the temperature profile and on the development of the HEN.

Step 3. Elimination of NIM. Identification of inefficient NIM points for two process configurations: before and after water reutilization. The inefficiency of the NIM points in the process is assessed by the exergy destroyed in direct heat exchanges. The effects of eliminating NIM in the temperature profile for both cases are studied and the corresponding HENs developed.

Step 4. Energy upgrading. Re-design of HENs to permit the integration of absorption heat pumps. AHP is an energy technology that can upgrade low temperature heat by exploiting the effect of pressure on an absorption–desorption cycle (Costa et al., 2009). Typically, the AHPs are implemented after the HEN has been designed. However, to increase steam savings, the technical and energy requirements of an AHP should be taken into account in the HEN design. The positioning of AHPs in a process must take into account the pinch point. The energy to be

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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). The technical feasibility of an AHP

depends on the target temperature of the cold stream and on the temperature lift required, which

is limited by inherent AHP constraints. The best option for implementing an AHP would require

either the heat source or receptor to be close to the pinch point.

Step 5. Condensate recovery. After steam savings are maximized by the other techniques, the

condensates that can be recovered are identified as well as the steam injections that can be

replaced by heat exchangers. A high condensate recovery rate in a process reduces the steam

required in the deareator.

Step 6. Energy conversion. The evaluation of cogeneration systems has to be done after the

thermal optimization. The objective is to define the proper size and the type of turbines.

Therefore, the steam required by the process has to be determined and also the available amount

that can be used only for power production. A combined process and utility analysis is performed

to adjust the steam pressure levels to the temperature profile of the process.

8.2.4 Implementation strategy and post-benchmarking

As the existing process configuration and operating conditions vary from process to process it is

important to develop a strategy for the implementation of energy enhancement programs in the

most advantageous way for each case. 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 pay back time (PBT) is used as the economic indicator.

$$PBT = I / [(R + S) - OC]$$
 (1)

I = Investment; R = Revenues; S= Savings; OC = operational costs

The investment costs are computed by the classical pre-engineering method based on multiplying factors (Ulrich and Vasudevan, 2004). These factors are based on the bare module cost (CBM), which vary depending on the equipment, its size and construction material. The CBM include 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:

- Direct and indirect expenses (i.e. material, labour), CBM_{steel}=3.18; CBM_{Ti}=11.2
- Contingency and fee, CTM = 1.18*CBM
- Auxiliary facilities costs (site development, off-site facilities), CGR = 1.3 *CTM

The multiplying factors depend on the type of equipment, its size and construction material.

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.

8.3 Application to case study

The methodology has been applied to an operating Kraft mill situated in Eastern Canada. It 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 where apart from pulp production, steam is exported to a nearby sawmill, municipal waste from the adjacent town is treated at the mill site, forest biomass is used as raw material and fuel and district heating is under study.

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 weak black liquor (BL) concentration (15% solids concentration) is performed in two steps; first, the BL is passed through a set of pre-evaporators (19% solids concentration) driven by recycled steam, and then it is sent to two parallel trains (55 % solids concentration) with post-concentrators (70% solids concentrators) driven by live steam. Drying is performed in two steps:

first, the pulp passe through a set of cylinders (dominion dryer) where water is evaporated by indirect heating, and then hot air is used to attain the final specification of pulp consistency (flakt dryer).

The replacement of the biomass boiler by a new one (twice the size of the current biomass boiler and producing steam at VHP: 8800kPa) is envisaged by the mill management with the objective of producing 35 MW of power. This new boiler is considered in the energy conversion measures.

8.3.1 Stage 1. Base case

Data gathering

There are two principal sources of information available in this case study: measure archived values for different years (2002-2003 and 2005 for steam; 2006 for water) and the PID's. 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.

Master diagram

Figure 4-3 gives an overview of the master diagram of the process indicating the number of available PIDs from which each section was developed.

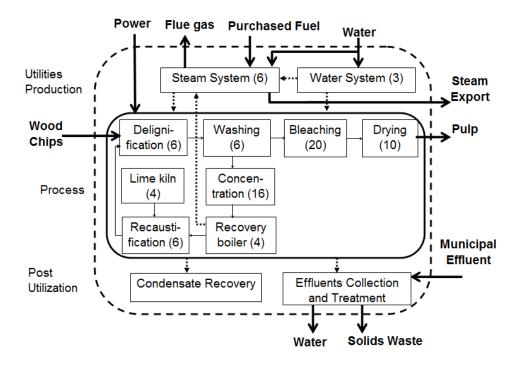


Figure 8-4. Overview of the master diagram.

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, 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.

Systems Analysis

Steam system. The steam required by the mill (Figure 8-5), 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 (PRV). Part of the clean condensate produced in the process is recovered and mixed with make up water at the deareator. Table 8-2 gives the steam consumption by process section for winter conditions. The steam consumption is reduced by 10% during the summer.

Table 8-2. Steam consumption by process section

Process section	GJ/adt
Delignification	3.99
Bleaching	1.75
Concentration	4.2
Drying	4.76
Water heating	1.54
Recaustification	0.57
Deareation	2.66
Steam export	0.69
Boilers, and other equip.	0.98

Total process consumption 21.14

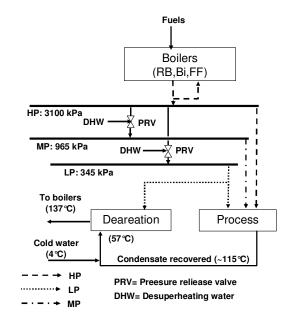


Figure 8-5. Steam Production

Fossil fuel is used to compensate for the poor performance of the boilers; however it should only be used to absorb the fluctuation of pulp production and seasonal variations of the steam demand. In theory, the Kraft process could be energetically self-sufficient (Mcilroy and Wilczinsky, 1999). The utilization of fossil fuel in the process is a sign of poor energetic performance.

Major inefficiencies 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 75%.
- Low efficiencies of the recovery boilers (58%) and of the biomass boiler (43%), below the typical Canadian average of 65%.
- Depressurisation of HP and MP steam in PRV's reducing the potential for electricity generation.

Water system. 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-Aragez (2008a) reported a percentage of 90% for their water study.

The water used in the process undergoes two pretreatments 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 ClO₂ making plant. The remaining 35 % of the feed water is only screened (screened water) and is used for cooling, vent gases scrubbing and house keeping. Table 8-2 gives the water consumption of process sections. The consumption of screened water varies appreciably between summer and winter. Chilled water for the ClO₂ making plant during the summer requires a large amount of screened water with the current equipment (absorption chiller and steam ejector). The overall water consumption increases 18% during summer.

The treated water is used at 5 temperature levels (Figure 8-6): 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 concentration section. 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 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 injections of steam in the hot water tank, and the
 mixing of streams at different temperature levels in the warm water tank.
- The effluents from the concentration 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 concentration effluents is almost 70°C.

Table 8-3. Water consumption by process section

Process section	m³/adt
Treated water	
Delignification & Washing	10,1
Bleaching	30,7
Concentration	1,0
Drying	10,7
Recaustification	2,0
Deareation	4,8
Steam exports	0,0
Boilers	0,2
Non process uses	4,6
Screened water	
Bleaching	24
Recaustification	4,6
Non process uses	11,1
Unaccounted water	6.4
Total process consumption	110,1

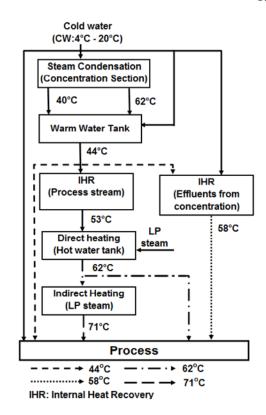


Figure 8-6. Water production

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. The starting points for the simulation flowsheet were the process master diagram and the utility systems.

Sections, such as bleaching, drying, black liquor concentration and the recovery boilers that affect directly steam and water consumption were modeled in detail. Simplified models were used for recaustification 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 posterior analyses.

The simulation has been validated by a comparison between simulated and measured data. In the case of the steam, the difference is of 0.9%, and in the case of water it is 6% (water intake). Table 8-4 and Table 8-5 show the overall steam and water balances obtained from the simulation.

Table 8-4 Overall water balance

Water Inputs		Effluents	
Section	m³/h	Section	m³/h
Water In wood chips		Water Out pulp	2.0
Water intake	2909.1	Effluents	3100.1
Direct steam injections		Water evaporated	52.6
Unaccounted	186.9	Condensate to the sewer	49.1
		Export	8.4
Total	3212.2	Total	3212.2

Table 8-5 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

Remarks

The base-case definition sets the foundation for all posterior analyzes. 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

8.3.2 Stage 2. Benchmarking analysis

Data compilation

All steam and water users have been identified after the characterization of both utilities systems. NIM points have been found in the hot water production and condensate recovery. Internal heat recovery measures have already been implemented by the mill to heat water (Figure 8-6) as well as water reutilization strategies within the bleaching section. Thirty cold streams and thirty hot streams have been identified.

The concentration of dissolved solids (DSC) in the water, which includes the organic and inorganic by-products from the chemical delignification of wood, is a constraint to be respected by the water sources.

Eighteen water sources and nineteen water sinks have been identified. There are streams that are also part of the energy analysis (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.

Comparison to the current practice

In the case of the Kraft process, the indicators are normalized to the ton of air dried (adt) and oven dried (odt) pulp produced. The difference in values expressed in either units is close to 10%.

An energy survey conducted at 49 P&P mills (Francis et al., 2006), 47 Canadian mills, 24 of which are Kraft processes, and 2 from the United States has been used for the task of comparison. The steam consumption of the mill (21.14 GJ/adt) is above the average (18.48 GJ/adt). The delignification, the BL concentration and the pulp bleaching sections are also below the average. The net thermal deficit, 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 the water usage and effluent production, the data used for comparison were taken from the average Canadian consumption in the 1990's given by Turner (1994). The overall water consumption (110.1 m³/adt) is clearly superior to the average (75 m³/adt). The effluents produced by the BL concentration (15.8 m³/adt) and bleaching (58.6 m³/adt) sections are above the average of 4.6 m³/adt and 48.5 m³/adt respectively.

The overall water and energy performance of the mill have been established by the comparison to the current practices. However, the causes of the inefficiencies and the appropriate way to correct them are not determined at this point.

New performance indicators

The energy and exergy content indicators are presented in Table 8-6. The Sankey diagrams of the exergy flows associated with the exergy supplied, destroyed and lost are shown in Figure 8-7.

- Flow 1: total exergy supplied by the combustion of fuels.
- Flow 2: destroyed exergy by the temperature difference between the gases of combustion and the required temperature for the production of HP steam.
- 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

Flows 5 and 6 encompass the total exergy currently used by the process ($Ex_{Proc} = 47MW$).

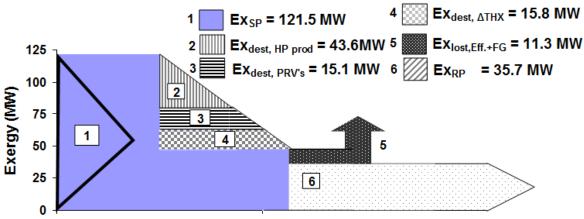


Figure 8-7 Sankey diagram of the exergy flows supplied to the process

Table 8-6 Energy and exergy data for the nominal process

	Energy Content (MW)	Exergy Content (MW)
Fuels combustion (Ex _{SP})	172	121.5
HP steam production	172	78
Steam utilization	172	62.8
Process consumption (Ex _{Proc})	172	47
Flue gases	11.8	4
Hot effluents	44.9	7.3
Water heating (Ex _{WTot})	37.1	12.2

Table 8-7 Exergy and energy indicators for the nominal process

	Energy	Exergy
	Indicators	Indicators
	(MJ/MJ)	(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	$ExC_T = .25$
Energy Conversion		ExC _{EC} =0 .61
Water heating	EC _{WTot} =0.22	$ExW_{Tot} = 0.26$

The energy supplied to the process by the combustion of fuels remains the same until this energy is consumed by the process, whereas exergy is destroyed along this same path. This aspect highlights the usefulness of considering exergy in the analysis. About 60% of the exergy supplied by fuels (ExC_{EC}) is destroyed which suggests that an important potential for energy conversion is untapped. The destruction of exergy in heat exchanges cannot be eliminated but could be significantly reduced by the optimization 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 exergy destroyed by the PRV's.

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

Targeting

Pinch Analysis

An analysis of the variation of heating requirement with respect to the ΔT_{min} was performed to obtain the appropriate ΔT_{min} . The construction of the composite curves was based on a ΔT_{min} of 10°C. This value has also been used in previous P&P studies (Savluescu and Alva-Argaez 2008). The composite curves for the process are shown in Figure 5-11. A minimum heating requirement (MHR) of 123 MW, a minimum cooling requirement (MCR) of 10MW and a pinch point (PP) of 71°C were obtained. The MHR suggest that the steam consumption of the process (172 MW) could be reduced by 49MW, 29% of the current requirement. Additional savings could be obtained by upgrading the energy of the heat rejected, after maximizing internal heat recovery, due to the implementation of absorption heat pumps.

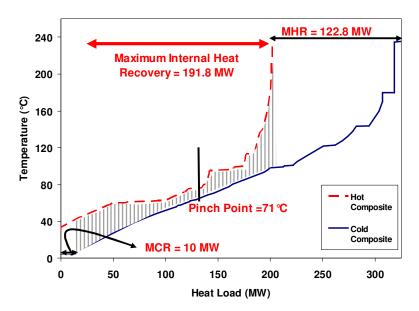


Figure 8-8 Thermal composite curves of the process

Water Pinch

The water composite curves are shown in Figure 5-12. The minimum water requirement (MWR) is $1000 \text{ m}^3\text{/h}$, the minimum effluent production (MEP) is $880 \text{ m}^3\text{/h}$, the maximum water reutilization is $1360 \text{ m}^3\text{/h}$ and the pinch point is found at DSC = 0 ppm. These targets suggest that the 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.

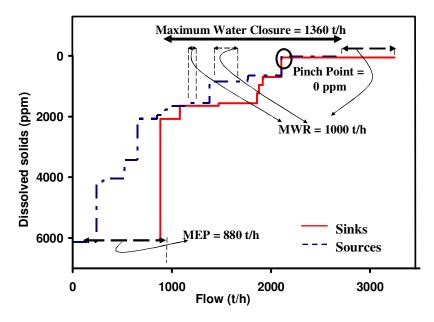


Figure 8-9 Water composite curves of the process

Synthesis

The steam and water consumptions are above the average industrial practice. The BL concentration 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 used for water and energy analysis, 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 consumption. All these issues are interrelated and should not be addressed individually. The analysis of the systems interactions is required so as to increase the energy efficiency of the process. The effects of water reutilization on the overall energy balance should be determined before developing improvement measures.

8.3.3 Stage 3. Interactions analysis

The cases developed in each step are presented in Figure 8-10. The modifications to the composite curves and the results for the cases developed are shown in Figure 8-15 and Table 8-8.

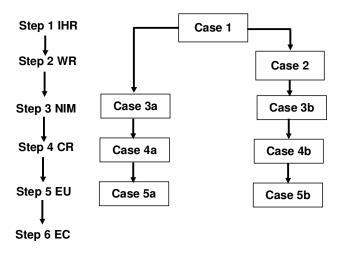


Figure 8-10. Interactions analysis procedure

Step 1 Internal heat recovery. The violations to the pinch rules for the process are:

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

A retrofit HEN (Case 1 in Table 8-8) has been developed based on the current process temperature profile (Figure 5-11). The HEN involves only the utilization of currently unused hot streams, bleaching effluents and flue gases, to reduce the steam used for water heating and in the

deareator. The increased utilization of heat from effluents, results in a reduction of their heat rejected (EC_E).

Heat recovery above the pinch from flue gases is an option to be privileged because of their high exergy content. An EC_{FG} value of zero for this and all subsequent cases shows that the available heat from flue gases is recovered.

Step 2 Water reutilization. Measures to decrease the water consumption by reusing different process effluents have been proposed (Mateos-Espejel et al., 2008b). The implementation of these measures reduces the steam demand of the process by 15.1 MW prior to IHR. These savings are achieved because the hot water production is decreased and the reused streams have a higher temperature than the water formerly used.

The effects on the thermal composite curves and MER after water reutilization are shown in Figure 8-15. The violations to the pinch rules after water reutilization are:

- 1. Utilization of a hot stream above the pinch point to heat a cold stream below it (15.2MW)
- 2. Utilization of a hot utility to heat a cold stream below the pinch point (3MW)
- 3. Utilization of a cold utility to heat a hot stream above the pinch point (19.2MW).

A retrofit HEN (Case 2) has been developed based on the modified process. The steam savings achieved by the water reduction measures have been included in the results shown in Table 8-8. Case 2 saves 29.7 MW of steam which is larger than in Case 1 and less surface area is required. The reduction of the rejected heat in the effluents (EC_E) is result of decreasing their production and of increasing heat recovery below the pinch. The required investment is lowered because less surface area for heat exchange is needed.

Step 3 Elimination of non-isothermal mixing. The most inefficient NIM points in the water and steam systems have been identified by quantifying the exergy destroyed in the corresponding operations. Two cases have been developed: Case 3a is based on the current process configuration, while Case 3b is based on the configuration after water reutilization. The measures

to eliminate NIM in the water systems (Case 3a) are shown in Figure 8-11b. The water at 62°C must be redirected to the hot water tank, and the fresh water must be preheated to 59°C by means of a process stream. This measure is not required after water reutilization because there is no longer need for fresh water addition to the warm water tank. The elimination of NIM in the deareator (Case 3a and 3b) is shown in Figure 8-12. The fresh water has to be preheated to 137°C by means of a process stream before it is mixed with the condensate recovered. These measures modify the composite curves, and thus the corresponding HEN.

The HEN developed in Case 3a makes a better usage of the low temperature heat available in the process below the pinch point. This is illustrated in the large reduction of rejected heat in the effluents (EC_E), from 0.26 in the current case to 0.12. The steam savings are largely superior to those obtained in Case 1. The reduction of the exergy destroyed in the warm water tank has a cascading effect reducing also the thermal inefficiencies downstream in the hot water tank and the need for indirect heating.

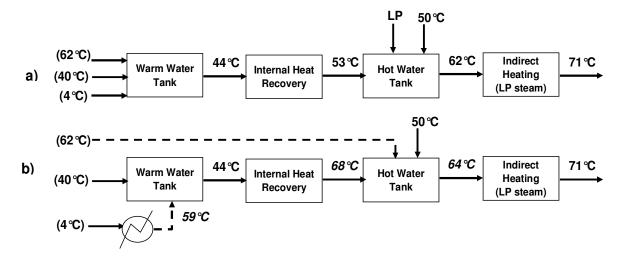


Figure 8-11. a) Current hot water production system; b) retrofit system

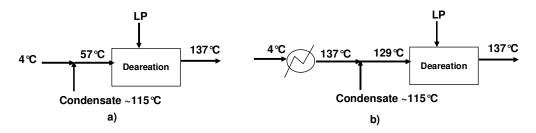


Figure 8-12. a) Current deareator system b) retrofit system

The developed HEN in Case 3b also makes a better usage of the low temperature energy below the pinch where EC_E is reduced to 0.13. The steam savings are increased by 8.4 MW but more area is required than in Case 2.

The improvement at the beginning of NIM-based paths (several NIM points connected as in Figure 8-11a) has a cascading effect downstream, which shifts the energy demands from high (steam) to low temperature heat sources (effluents). Therefore, the steam savings achieved by internal heat recovery are increased.

Step 4 Energy upgrading. The HENs which have been re-designed are Case 3a and 3b. The new AHP compatible designs are represented by Case 4a and Case 4b.

The HEN for Case 3b and 4b are shown in Figure 13 and 14. The surface area required is larger than in the previous cases because the $\Delta T_{approach}$ of the process to process heat exchangers decreases. The heat loads of the streams close to the pinch have been left available for the posterior implementation of AHPs. These options become interesting when power production is also part of the process retrofit because the more steam is saved in the process, the more can be used to produce power.

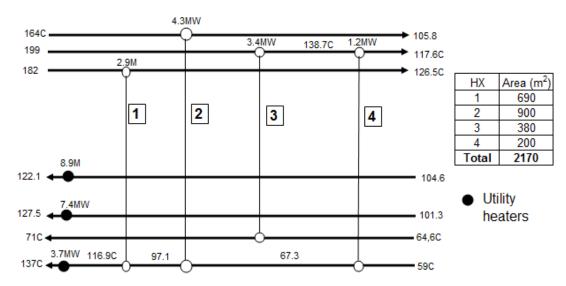


Figure 8-13 Case 3b: network design above the pinch

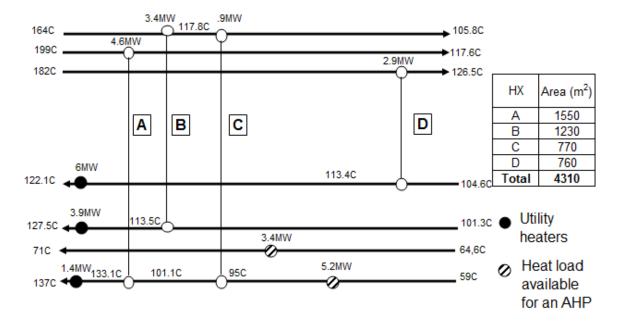


Figure 8-14 Case 4b: network design above the pinch

Step 5 Condensate recovery. Two measures have been identified to increase condensate recovery: the replacement of steam injection used to heat whitewater (aqueous suspension of particles of fibers entrained as water is drained from the pulp before drying) by a heat exchanger and collection of the condensates produced in the recaustification unit. These measures can be implemented for the process without (Case 5a) and with (Case 5b) water reutilization. The results for both cases diverge on two points from Cases 4a and 4b: the reduction of the steam consumption for deareation (2.3 MW) because less cold water is required; and the increase of the surface area required due to the reduction of the $\Delta T_{approach}$ in the associated exchangers.

Step 6 Energy conversion. The implementation of two turbines has been proposed by Cakembergh-Mast *et al* (2009). Case 5b is the basis for the cogeneration implementation because the more steam savings, the more steam can be utilized to produce power. 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. A maximum production of 44.4 MW is obtained.

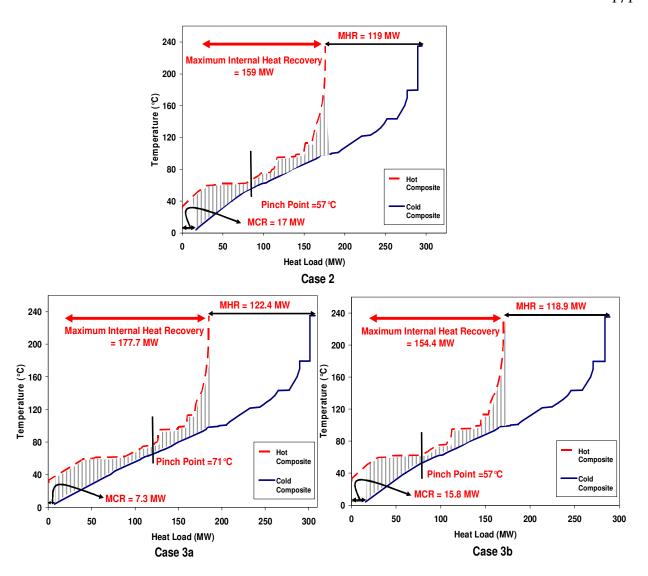


Figure 8-15 Thermal composite curves modifications

Table 8-8 HEN performances

	Steam savings (MW)	Surface area (m²)	ECE
Current	-	-	.26
Case 1	22.5	3580	0.2
Case 2	29.7	2120	0.18
Case 3a	34.7	4641	0.12
Case 3b	38.1	2990	0.13
Case 4a	34.7	5860	0.12
Case 4b	38.1	5130	0.13
Case 5a	37	6080	0.12
Case 5b	40.4	5350	0.13

Results

The pinch point is reduced to 57°C after water reutilization. The MCR increases because the hot water requirement is decreased. In consequence, part of the cold water used for steam condensation in the BL concentration section becomes an additional cooling demand for the overall process. The modification to the MER for the cases where NIM is eliminated is result of switching the involved energy demands from above the pinch to below it.

All HEN developed used the heat content from the flue gases because their high temperature makes them suitable to heat cold streams above the pinch point. However, the principal steam savings occur by recovering the available heat below the pinch as shown in the reduction of the rejected heat in the effluents (EC_E) for all cases. The cases which consider water reutilization (2, 3b, 4b, 5b) produce more steam savings and require less surface area. The reason is a reduction of the energy required by the process that is shown in the decrease of the maximum internal heat recovery (Figure 8-15). The elimination of NIM also has a positive effect on the steam savings although there is a penalty in the surface of exchange required. NIM elimination is particularly important for the cases without water reutilization as the savings substantially increases between Case 1 and 3a. The surface area required by the HEN in Cases 4a and 4b is larger because the temperature approach ($\Delta T_{approach}$) for the exchangers used above the pinch is reduced. The larger surface area of the HEN in cases 5a and 5b is due to the replacement of steam injection above the pinch by heat exchangers to increase the condensate recovery rate and thus reducing the steam needed by the deareator. The design of a cogeneration system should consider the production and utilization of steam in the process. Therefore, the turbines should be implemented after all steam measures have been accomplished. In addition, the power production potential is increased (44.4 MW), taking into account the installation of the new biomass boiler.

The last stage of the methodology encompasses an implementation strategy for the energy saving measures selected on the basis of economic and technical constraints.

8.3.4 Implementation strategy and postbenchmarking

A three phase strategy has been proposed:

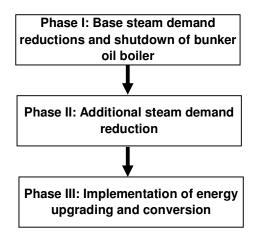


Figure 8-16 Implementation methodology

All prices are in Canadian dollars and have been indexed to 2008. The cost of the steam 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 \$/m³ and the cost of effluent treatment 0.1 \$/m³ (Gullichsen and Fogelholm, 1999; Lovelady and El-Halwagi, 2007). The price of electricity sold to the grid is 90 \$/MWh (Cakembergh-Mas et al., 2009b). The operating time of the mill is 8400 hours/a.

Phase I. Base steam demand reduction and shut down of the fossil fuel boiler

The maximum production capacity and the yearly average utilization of steam made available by the mill were computed (Table 8-9). 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.

Table 8-9. Average and maximum utilization of steam

<u>.</u>	Max	imum	Ave	erage
Fuel used	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

The measures involved in this phase encompass the condensate recovery, water reutilization and one internal heat recovery project. The measures for increasing the condensate recovery rate must be implemented first because they do not affect any part of the process other than the deareator. The proposed measures are:

- 1. Replacement of steam injection by a heat exchanger for whitewater heating
- 2. Condensate recovery in the recaustification section.

The implementation of water usage reduction measures are the core of the process energy efficiency enhancement because the increase of water reutilization causes a rise in the effluents temperatures and a decrease of the utility steam used to heat water. This modifies the energy balance of the mill. Thus water reduction measures have been implemented before internal heat recovery.

- 3. Reutilization of the effluents from the BL concentration section, in the pulp washing and in the recaustification sections
- 4. Reutilization of whitewater 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. The heat recovery from the flue gases requires a hot oil recirculation system in which the oil is used as energy carrier from the flue gases to the process streams (Mostajeran-Goortani et al., 2009).

Shutting down the fossil fuel boiler is a feasible and attractive option for the mill because the high price of this fuel makes the overall PBT (0.7a) 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.

Table 8-10 Phase I Economic Analysis

	Steam saved (MW)	Water saved (m3/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

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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 would liberate steam capacity for cogeneration and the extra generation of revenues for the mill.

Phase II. Additional steam demand reductions

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

- 8. Preheating of whitewater by the bleaching effluents
- 9. BL concentration by the utilization of flue gases

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

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 and Paris (2009) have 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.

Phase III. Energy upgrading and conversion

The AHPs have been used to upgrade the heat of effluents that has not been used for internal heat recovery. Bakhtiari et al (2009) proposed the implementation of two AHPs:

- 10. Upgrading the heat from bleaching effluents to reduce the steam consumed for water and whitewater heating and, by the deareator,
- 11. Upgrading the water effluents from the chemical preparation section during summer to reduce the cooling demand as well as the steam consumed by the deareator and the BL concentration section.

The energy conversion measures are:

- 12. Reduction of LP steam from 345 kPa to 220 kPa,
- 13. Reduction of the pressure of the steam used for drying (from HP to LP) and for BL concentration (from MP to LP).
- 14. Implementation of the two turbines (condensing and backpressure), after all steam savings have been achieved.

The implementation of the AHPs is expensive and with a long PBT (Table 7-9) because biomass is, for the time being, a very inexpensive fuel. The operating cost of cogeneration (16.1 M\$/a) is the cost of steam produced from biomass and used only for power production. The investment required for both turbines is 14.4 M\$, generating revenues of 33.7M\$/a by the sale of electricity to the grid. The low PBT (1a) makes the implementation of this phase very attractive.

Table 8-11 Phase III Economic Analysis

	saved	Water saved (m³/h)		Inv. (M\$)	Sav. & rev. (M\$/a)	Operat. Cost (M\$/a)	P.B.T. (a)
EU	5.6	540	-	4.3	.6	-	7
EC	-		44.4	14.4	33.7	16.1	.8
Total Phase III	5.6	540	44.4	18.7	34.3	16.1	1

The overall implementation with a PBT of one year is economically attractive at the current price of energy (Table 7-11). Further increases in the price of biomass and of electrical power which can be exported and, the probable creation of carbon credits will reduce the PBT.

Table 8-12 Economics of the full strategy implementation

	Steam saved	Water Saved	Power	Investment	Revenues	PBT
	(MW)	(m ³ /h)	(MW)	(M\$)	(M\$/a)	(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	44.4	18.7	18.2*	1
Total	46.1	1080	44.4	31.6	31.8	1

^{*}Profits = revenues – operating cost

The buyer's constraint for the sale of electricity is a minimum of 35 MW. This target can be surpassed in all seasons taking into account the implementation of the new biomass boiler and the energy improvement measures. Mateos-Espejel et al (2009a) determined that a smaller boiler (steam production: 116 t/h) would be required to produce 35 MW of power. This consideration would reduce the investment needed.

Post-benchmarking

The changes of the indicators used for benchmarking are given in Table 7-10. 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 8.1GJ/adt to 2.5 GJ/adt. The mill considerably reduces

its reliance on purchased fuel. The water savings will be $1080 \text{ m}^3/\text{h}$ ($37.02 \text{ m}^3/\text{adt}$) and the mill water consumption should be $73.1 \text{ m}^3/\text{a.d.t}$, just below the Canadian average of $75 \text{ m}^3/\text{adt}$.

The energy content of the effluents is reduced from 0.26 to 0.11 because their production decreased and their energy content is recovered. There is a substantial reduction of steam for water heating due to water reutilization and internal heat recovery. The energy content of the flue gases is completely recovered by cold streams above the pinch point.

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 44.4 MW of power.

Table 8-13 Postbenchmarking: indicators variation

Indicator	Current	Enhanced	⊿%	Reference
Current steam consumption (GJ/adt)	21.1	15.5	26.6	18.5
Water consumption (m ³ /adt)	110.1	73.1	33.6	75
Net thermal deficit (GJ/adt)	8.1	2.5	69.1	2.4
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

8.4 Conclusions

The improvement of the process by applying the unified methodology results in substantially more steam savings than by applying individually the typical techniques that it comprises.

The first two stages, base case definition and benchmarking, set the foundation for all analyses and 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 analyze the efficiency of the current steam production system as well as the exergy losses associated with a lack of internal heat recovery and water reutilization.

The energy-water interactions are the core of the analysis as all cases (2, 3b, 4b, 5b) where water is saved resulted in higher steam savings and lower surface area required by the HEN. The elimination of NIM increases the heat recovery below the pinch point.

The implementation of energy upgrading and conversion devices generates revenues from the sale of electricity to make the energy programs even more attractive. The upgrading of the recovery boilers, whose efficiency is below the Canadian average, should be envisaged so as to increase the steam available for power production. This project would also reduce the size of the new boiler required to produce 35 MW of electricity. The over-sizing of the boiler must be avoided by previously improving the energy efficiency of the process.

The fact that energy, water and exergy factors are considered give a broader view of the process energy efficiency because all driving forces are analyzed in terms of the quantity used, mode of employment and their quality. 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 shutdown of the fossil fuel boiler and the production of power.

The application of mathematical optimization on the third stage could increase the steam savings and that will be the focus of future work.

The final result of the unified methodology is an eco-friendly process that does not require fossil fuel for producing steam; its water and steam consumptions are below the Canadian average and it generates large revenues from the production of green electricity from biomass.

GENERAL DISCUSSION

Base Case

The nominal conditions of the process have been established based on several sources of information such as measured data, and the PIDs.

Several factors that affect the energy efficiency can be identified at this early stage: non isothermal mixing points, the low efficiency of the boilers, the utilization of fossil fuel, the absence of cogeneration and water reutilization. However, a diagnostic of the efficiency of the process cannot be established, as more detailed evaluations are required.

Benchmarking analysis

The comparison to the current industrial practice is complemented by the utilization of new energy and exergy indicators. The exergy is used to compute the efficiency of the energy conversion and the utilization in the process.

The identification of the streams involved in both the energy and water analysis is critical to reveal energy systems interactions.

The targeting by Pinch Analysis and Water Pinch sets the limits of internal heat recovery and water reutilization at the current conditions of the process.

Several guidelines have been proposed to improve the most inefficient sections of the process and to analyze the effects of the systems interactions. Cogeneration emerges as an opportunity to reduce the large amount of destroyed exergy in the pressure release valves.

Systems interactions analysis

The application of several enhancing techniques modifies the systems configuration and the thermal balance of the process.

The elimination of non-isothermal mixing results in a better usage of the heat below the pinch point and a lesser surface requirement by the HEN.

The heat exchangers network should be designed to integrate absorption heat pumps (AHP). However, as a consequence of this, the surface of some heat exchangers increases. Nevertheless, AHP in the context of trigeneration becomes profitable.

Implementation strategy

Technical, thermal and economic constraints are considered. Three objectives must be accomplished by the implementation strategy at this step: shutdown of the fossil fuel boiler, liberating steam capacity for power production and implementation of a trigeneration system (power production and energy upgrading).

The revenues obtained from the elimination of fossil fuel and from the production of power make the strategy very attractive.

CONCLUSIONS AND RECOMMENDATIONS

The main objective of this thesis was to propose energy efficiency measures that take into account the interactions of the process energy systems. A unified methodology to accomplish that task has been developed. It consists of four steps:

- Definition and characterization of the base case
- Benchmarking analysis
- Systems interactions analysis
- Implementation strategy

The development of a computer model in a water-energy oriented perspective is necessary to quantify the systems interactions and to analyze the feasibility of energy improvement measures.

The utilisation of thermal energy, water and exergy to evaluate the process gives a broad perspective for the detection of inefficiencies. The computation of the exergy destroyed and lost is essential to quantify the effects of the low rate of water reutilization, lack of internal heat recovery and, the inefficiencies in the production and utilization of the utilities.

The identification of the systems interactions is the central point of the unified methodology. The modifications that occur to the thermal composite curves and the possible integration of absorption heat pumps must be indentified prior to the development of a retrofit heat exchanger network (HEN).

The proposed measures are the result of the interactions analysis. Therefore, they are complementary. Individual analyses might give solutions mutually exclusive, as only one aspect of the energy efficiency is studied.

The improvement of the process by applying the unified methodology results in substantially more steam savings than by applying individually the typical techniques that it comprises.

The consideration of all driving forces of the process gives a broader perspective of the process energy efficiency. The improved process does not consume fossil fuel, water heating is performed by internal heat recovery and power is produced from biomass.

The application of this kind of methodology should become a standard procedure. The energetic improvement is considered in a global view and taking into account the principal driving forces of the process.

Original contributions

Development of a novel unified methodology:

- Consideration of energy, water and exergy
- Application of several energy enhancing techniques
- Pre- and Post- Benchmarking analysis
- Systems Interactions analysis
- Technical, economic and energetic aspects considered in the development of an implementation strategy

Recommendations for future research

Benchmarking analysis

To evaluate the exergetic efficiency of all unit operations in order to quantify the effects of poor equipment operation or bad isolation, fouling, etc

Interactions analysis

To develop a mathematical algorithm for heat exchanger networks design that includes the integration of absorption heat pumps, water reutilization aspects and elimination of non-

isothermal mixing. The expected results are an increase of the steam savings and revenues generated. The exergetic efficiency can also be included in the algorithm.

Biorefining

The unified methodology can be applied in the analysis for converting Kraft mills to biorefineries. The interactions between the two processes should be analyzed in order to propose measures for fulfilling the increasing energy demand by the appropriate utilization of energy enhancing techniques rather than by purchasing external fuels.

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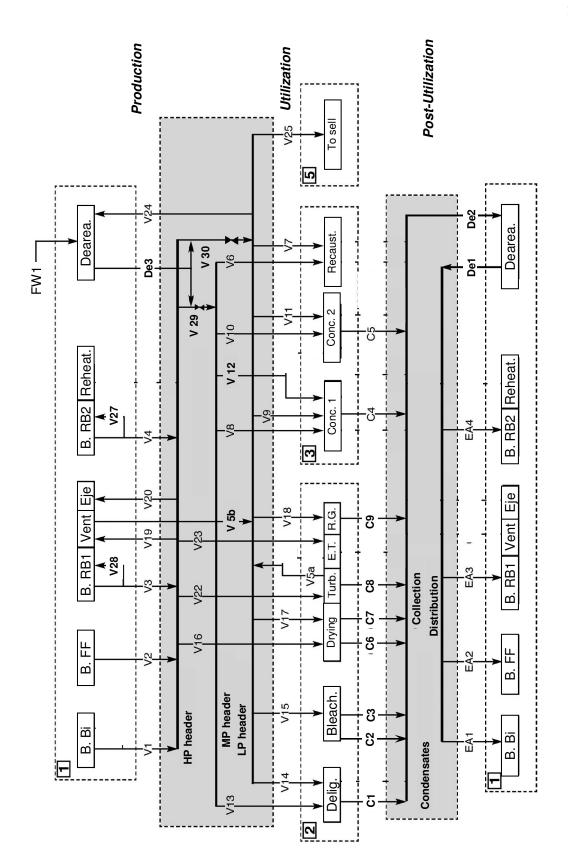
APPENDIX 1 – Detailed steam production and utilization mass balances

HP Steam	IP Steam		Mass flow (t/h)		
ID	Description	Sim.	Raw data	% diff.	
V1	Biomass boiler (BI) - Steam production	64,8	64,7	0,00	
V2	Fossil fuel boiler (FF)- Steam production	27,5	29,5	6,85	
V3	Recovery boiler (RB1) - Steam production	88,8	89,0	0,00	
V4	Recovery boiler (RB2) - Steam production	55,8	55,7	0,07	
	Total steam production	236,8	238,9	0,90	
V29+V30	to PRV for MP and LP steam production	180,7	182,5	1,01	
v26	Boilers -Soot blowing RB1	2,67	2,7	1,11	
v27	Boilers -Soot blowing RB2	1,73	1,7	1,76	
V16	Dryer-Flakt	28,2	28,0	0,73	
V22+V23	Drying - Turbine	20,3	20,7	2,10	
V19	Ventilator - RB	3,3	3,3	0,43	
	Total steam consumption	236,8	238,9	0,87	

MP Steam		Mass flo	ow (t/h)	
ID	Description	Sim.	Raw data	% diff.
V29	HP to MP steam	70,8	69,4	2,07
De3.1	Desuperheating water	14,1		
	Total steam production	84,9		
V6	Recaust - Lime kiln	1,0	1,1	9,18
V8	Concentration 1 - High solids conc.	12,2	13,2	7,27
V13	Delignification	54,4	52,3	4,16
V25	To sell	8,4	8,4	0,00
V20	Ejector	2,0	2,2	9,59
V12	Concentration 1 - Stripper	6,8	6,8	0,00
	Total steam consumption	84,9	84,0	1,08

LP Steam		Mass flo	ow (t/h)	
ID	Description	Sim.	Raw data	% diff.
V30	HP to LP steam	109,8	113,1	2,92
V5a +V5b	Drying turbine / ventil. RB	23,6	24,0	1,87
De3.2	Desuperheating water	21,7		
	Total steam production	155,07		
V15	Bleaching	13,8	15,3	9,50
V17	Drying- Dominion	12,7	13,8	8,32
V14	Water heating	20,3	22,4	9,40
V9	Concentration 1	15,3	17,1	10,54
V10 + V11	Concentration 2 - High solids conc.	21,1	20,5	2,94
V7	Recaustification	3,9	3,9	0,00
V24	Deareation	35,8	41,4	13,49
	Chemical department steam	10,0	11,1	0,10
V22+V23	Drying - heating purposes foudrinier	20,1	20,7	2,88
V18	Drying - exchanger glycol	2,1	2,1	0,00
	Total steam consumption	155,07		7,85

Condensate recovered					
ID	Description	Mass flow (t/h)			
C1	Delignification	20,3			
C2	Water heating	9,3			
C3	Bleaching	15,6			
C4	Concentration 1	19,6			
C5	Concentration 2	10,6			
C6	Drying- Flakt	18,3			
C7	Drying- Dominion	9,2			
C8	Drying - exchanger glycol	2,1			
C9	Drying - Heating purposes	4,8			
De2	Total condensate recovered	109,9			



APPENDIX 2 – Detailed water production and utlization mass balances

Water	input to the system					
	5	Reconciled	Raw data	%	PID	%
ID	Description	(m³/h)	(m³/h)	diff.	(m ³ /h)	diff.
w27	Treated water	1749,7	2024,0	13,6	-	-
w28	Screened water	1159,4	1072,0	8,2	-	-
	Total	2909,1	3096,0	6,0		

Treated water utilization

Cold water utilizati	on
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ID	Description	Reconciled	Raw data	%	PID	%
יוו	Description	(m³/h)	(m³/h)	diff.	(m ³ /h)	diff.
FW1	Deareation - Make up water	138,7	144,5	4,1	133,4	4,0
W10	Bleaching - gas washing, mixers	42,0	44,8	6,2	23,9	76,1
w11	Bleaching - Prewash (HE5) Hot water	122,8	66,8	83,8	122,8	0,0
W13	Drying - Vac. Pump; Bleach- Ch. Pr.	196,3	86,8	126,1	276,5	29,0
w19.1	Make up water (warm water tank)	100,8	88,26	14,2	-	
w19.2	Water by passed	134,0	134,0	0,0	134,0	0,0
w20	Warm water prod. Conc. 2 - Cond. (HE1)	262,2	265	1,1	-	
w21	Warm water prod. Conc. 1 - Cond. (HE2)	293,8	312	5,8	-	
w22	Warm water prod. Concpre.ev Cond.(HE3)	446,9	313,4	42,6	-	
	Total	1737,3	1455,6	19,4	690,5	151,6

Warm	water utilization					
ID	Description	Reconciled (m ³ /h)	Raw data (m ³ /h)	% diff.	PID (m³/h)	% diff.
w2	Washing	57,9	77,2	24,9	59,0	1,8
w12	Bleaching - Prewash	108,2	64,8	67,0	-	
w23.1	To Internal heat recovery (HE4)	770,9	-		770,9	0,0
w24	Over-pressed hot water (from HE 6)	108,0	-		108,0	0,0
w14	Recaustification	58,6	-		57,42	2,1
	Total	1103,7	142,0		995,3	10,9

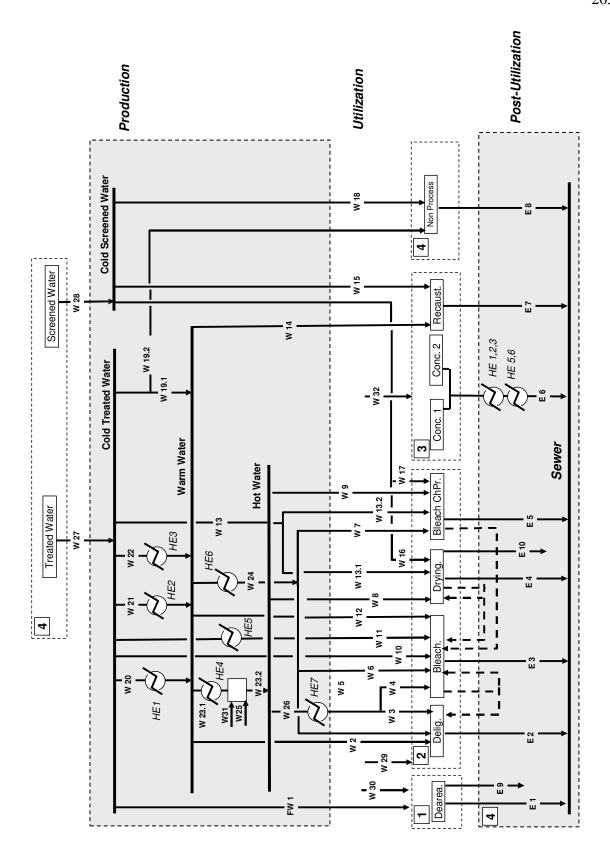
Hot wa	iter production					
	.	Reconciled	Raw data	%	PID	%
ID	Description	(m ³ /h)	(m³/h)	diff.	(m ³ /h)	diff.
w23.1	To Internal heat recovery (HE4)	770,9	-		770,9	0,0
w31	LP steam to direct water heating	10,8	10,8	0,2	-	
w25	Process steam from Delignification	1,5	-		1,5	0,0
w23.2	Total	783,2	10,8		772,4	1,4

Hot wa	iter utilization					
ID	Description	Reconciled (m ³ /h)	Raw data (m³/h)	% diff.	PID (m³/h)	% diff.
w26	To HE7 (indirect heating LP steam)	541,7	-		-	
w3	Washing	161,8	158,4	2,1	-	
w4.1	Bleaching- Washer 1	102,0	10,8	844,4	128,0	20,3
w4.2	Bleaching- Washer 2	93,2	61,8	50,8	127,9	27,2
w4.3	Bleaching- Washer 4	180,0	112,8	59,6	180,0	0,0
w9.1	Bleaching - Chem prep.	4,8	3,3	44,8	4,7	2,1
w9.2	Bleaching - Chem prep. NaOH	15,5	5,7	172,5	14,0	10,6
w8.1	Drying	215,6	204,5	5,5	264,0	18,3
w8.2	Drying - Aux tank white water	6,2	6,1	2,1	300,0	97,9
w18.2	Drying - miscelaneous	4,2	4,1	2,1	4,1	2,1
	Total	783,2	567,4	38,0	1022,7	23,4

Screen water utilization Cold water

Cold w	rater					
	Description	Reconciled	Raw data	%	PID	%
ID	Description	(m³/h)	(m³/h)	diff.	(m ³ /h)	diff.
w18.1	Drying - glycol	7,7	-		7,98	3,8
w18.3	Pumps Sealings	11,0	-		11,4	3,8
w18.4	Domestic, Hoses, Vent and Cooling	301,0	-		301,02	0,0
w15	Reacustification - Lime kiln	132,8	138,1	3,8	-	
w16	Pumps	6,5	-		6,5	0,6
w17.1	Bleaching - Cooling absorption tower	180	180	0,0	-	-
w17.2	Bleaching - Cooling ClO2 generator	540,4	543,8	0,6	-	
	Total	1179,2	861,8	36,8	326,9	

Efflue		
ID	Description	Reconciled (m ³ /h)
E1	Boilers	12,0
E2	Delignification	19,4
E3	Recaustification	133,0
E4	Drying	227,4
E5	Bleaching - Chem. Prep	755,3
E6	Bleaching	951,0
E7	Screen water	457,8
E8	Concentration	376,7
E9.1	Water evaporated (boiler,dryer)	52,6
E9.2	Water Out pulp	2,0
E10	Condensate to the sewer	38,1
	Total	3025,3



APPENDIX 3 – List of Publications

ARTICLES ET NOTES DANS JOURNAUX AVEC COMITÉ DE LECTURE Soumis (5)

Mateos-Espejel, E., Savulescu, L., & Paris J. « Base Case Process Development for Energy Efficiency Improvement, Application to a Kraft Pulping Mill: Part I Definition and Characterization», Chem. Eng. Research and Design. (13/09/09).

Mateos-Espejel, E., Savulescu, L., Marechal, F., & Paris J. « Base Case Process Development for Energy Efficiency Improvement, Application to a Kraft Pulping Mill: Part II: Benchmarking analysis», Chem. Eng. Research and Design. (13/09/09).

Mateos-Espejel, E., & Paris J. « Implementation strategy towards an energy efficient Kraft mill», Applied Thermal Engineering (15/09/09).

Mateos-Espejel, E., Savulescu, L., Marechal, F., & Paris J. « Systems interactions analysis for the retrofit of a typical Kraft process», Energy, the international Journal (12/10/09).

Mateos-Espejel, E., Savulescu, L., Marechal, F., & Paris J. « Unified methodology for thermal energy efficiency improvement: Application to Kraft process », Chemical Engineering Science (12/10/09).

Parus (2)

- (1) Marinova, M., E. Mateos-Espejel, N. Jemaa & J. Paris . "Addressing the increased energy demand of a Kraft mill biorefinery" Chem. Eng. Research and Design. V87 (9),1269-1275 (2009)
- (2) Mateos-Espejel, E., Pereira, L.M., Marinova, M., & Paris, J. "Energy and Water in the Pulp and Paper Industry: The Two Solitudes" Chemical Engineering Transactions Vol. 11. 695-700 (2007)

COMPTES RENDUS DE CONFÉRENCES AVEC COMITÉ DE LECTURE Parus (11)

- (1) Mateos-Espejel, E., Alva-Argaez, A., Savulescu, L., & Paris, J., "From Kraft Mills to Forest Biorefinery: an Energy and Water Perspective", 2nd NWBC, 108-112, Helsinki (2009)
- (2) Marinova, M., Mateos-Espejel, E. & Paris, J., "Challenges before the Canadian Biorefinery: A case study", 2nd NWBC, 103-107, Helsinki (2009)
- (3) Marinova, M., Mateos-Espejel, E. & Paris, J., "Sustainability of the Forest Biorefinery", Proceed. SEEP2009, 246-51, Dublin (2009).
- (4) Mateos-Espejel, E., B. Goortani-Mostajeran and J. Paris "Intégration de la cogénération d'énergie dans une usine de pâte et papier" IXème colloque franco-québecois sur la thermique des sytèmes, 227-232, Lille (2009)
- (5) Mateos-Espejel, E., M. Marinova, D. Diamantis, L. Fradette & J. Paris, "Strategy for converting a conventional Kraft Pulp mill into a sustainable Green Mill", 10th World Renewable Energy Congress WREC X., 176-80, Glasgow (2008).
- (6) Mateos-Espejel, E., M. Marinova, S. Bararpour & J. Paris, "Energy Implications of Water Reduction Strategies in Kraft Process. Part I: Methodology", PAPTAC 94th Ann. Mtg., A-57-61, Montréal (2008)
- (7) Mateos-Espejel, E., M. Marinova, S. Bararpour & J. Paris, "Energy Implications of Water Reduction Strategies in Kraft Process. Part II: Results", PAPTAC 94th Ann. Mtg., A-219-23, Montréal (2008).
- (8) Marinova, M., Mateos-Espejel, E., Bakhtiari, B., Paris, J. "A New Methodology for the Implementation of Trigeneration in Industry: Application to the Kraft Process" First European Conference on Polygeneration: Technologies and Application, 333 -351 Tarragona (2007)
- (9) Mateos-Espejel, E., Marinova, M., Maréchal, F., & Paris, J. "Analyse Énergétique d'Évaporateurs par la Méthode de la Double Représentation" Presenté au VIII ème colloque franco-québecois sur la thermique des sytèmes, 257-262 Montréal (2007)

- (10) Bakhtiari, B., Mateos, E., Legros, R., & Paris, J. "Integration of an Absorption Heat Pump in the Kraft Pulping Process: Feasibility Study" PAPTAC 93rd Ann. Mtg , 235 239 Montréal, (2007)
- (11) Pinto, R., Mateos-Espejel, E., Perrier, M., & Paris, J. "Effect of variability on the thermal efficiency of a Kraft mill evaporation unit", Proceed. Control Systems/Pan Pacific Conf., 207-12, Vancouver (2008)

AUTRES CONFÉRENCES ET PUBLICATIONS

Faites (12)

- (1) Mateos-Espejel, E., Marinova, M., B. Goortani-Mostajeran & J. Paris " Eco-Industrial Cluster centered on a Kraft mill in rural Canada" World Congress of Chemical Engineering WCCE8, CD room No. 0862 Montreal (2009)
- (2) B. Goortani-Mostajeran, E. Mateos-Espejel & J. Paris "Heat recovery from stack gases in Kraft process to reduce steam demand" World Congress of Chemical Engineering WCCE8 Montreal, Cd Room 0863 (2009)
- (3) Marinova, M., Mateos-Espejel, E. & Paris, J., "The Forest Biorefinery, an Opportunity, not a Panacea: The Canadian Context", PRS2009, Kuopio, Book of abstracts (2009)
- (4) Mateos-Espejel, E., Marinova, M. & Paris, J. "Minimizing increased steam demand in a Kraft-process based biorefinery", Canadian Pulp and Paper Network for Innovation in Education and Research, Poster Session, PAPTAC, Montréal, (2009)
- (5) Mateos-Espejel, E., M. Marinova, B. Baktiari, L. Savulescu & J. Paris, "Integrated methodology for energy and water reduction in the Kraft process", COST 36 International Conference "Modeling and Simulation in the Pulp and Paper Industry, Madrid (2008).
- (6) Pinto, R., Mateos-Espejel, E., Perrier, M., Paris, J. "Control system for a Kraft mill evaporation section to reduce variability and enhance the thermal efficiency", "Canadian

- Pulp and Paper Network for Innovation in Education and Research, Seminar Session", PAPTAC Montreal (2008)
- (7) Quiron-Blais, O., **Mateos-Espejel**, E., Trepanier, M., Fradette, L., Legros, R. & J. Paris, "Forest Biorefinery-Based Eco-Industrial Clusters in Canada: The Energy Challenge", POLYCITY General Meeting, Barcelona (2008)
- (8) Marinova, M., **Mateos-Espejel, E.**, Bakhtiari, B. & Paris, J., "Guidelines for the Implementation of a Trigeneration Unit in a Kraft Process", Paptac Western Branch Conf., Edmonton (2008).
- (9) **Mateos-Espejel, E.**,"Combined thermal, mass and exergy analysis: Unified Optimization Methodology" Canadian Pulp and Paper Network for Innovation in Education and Research, Poster Session, PAPTAC Montréal, (2007)
- (10) Mateos-Espejel, E., Bakhtiari, B., Marinova, M., Legros, R., & Paris, J. "Implementation of Trigeneration in a Kraft Process" COST-36 Meeting and Symposia", Munich, (2007)
- (11) Mateos-Espejel, E., Charron, D., & Paris, J. "L'Analyse de Pincement comme Outil de Diagnostique pour améliorer l'efficacité énergétique d'une usine de pâte Kraft" Presenté à la Conférence ATPPC-Division de la Vallée de l'Outaouais Montebello, Qc., (2006)
- (12) Mateos-Espejel, E., Meyer, P., Maréchal, F., & Paris, J. "Pinch Analysis as a Diagnostic Tool for Energy Efficiency Enhancement in a Kraft Mill" Presented at the "58th Canadian Chemical Engineering Conference", Sherbrooke, Qc., (2006)

RAPPORTS TECHNIQUES

Soummis(2)

(1) Marinova, M., E. Mateos-Espejel, N. Jemaa & J. Paris, "How to Face the Energy Demand of a Kraft Pulp Mill-Based Biorefinery? The Hemicelluloses Extraction Case", PSR soumis 01/12/08

(2) **Mateos-Espejel, E.,** M. Marinova, B. Mostajeran-Goortani, & J., Paris, "Eco-Industrial Cluster Centered on a Kraft Mill in Rural Canada" PUR soumis 15/12/08

Parus (9)

- (1) B. Mostajeran-Goortani, E. Mateos-Espejel & J. Paris, "Heat Recovery from Stack Gases in a Kraft Process to Reduce Steam Demand", PUP 955 (2009).
- (2,3) Mateos-Espejel, E., Marinova, M., S. Bararpour & J. Paris, "Energy Implications of Water Reductions Strategies in a Kraft Process",

8a. "Part. I, "Methodology", PSR 617 (2009)

8b. "Part. II, "Results", PSR 618 (2009)

- (4) R. Pinto-Pires, **E. Mateos-Espejel**, M. Perrier & J. Paris, "Effect of Variability on the Thermal Efficiency of a Kraft Mill Evaporation Unit" PUP 949 (2008).
- (5) Marinova, M., E. Mateos-Espejel, B. Bakhtiari & J. Paris, "Guidelines for the implementation of a Trigeneration Unit in a Kraft Process", PSR603 (2008).
- (6) Mateos-Espejel, E. M. Marinova, F. Marechal & J. Paris,
 - "Analyse énergétique d'évaporateurs par la méthode de la double représentation", PUR 945F (2008),
 - "Analysis of Evaportors using the Dual Representation Method", PUR 945E (2008).
- (7) Mateos-Espejel, E., M. Marinova, L. Fradette & J. Paris, "École Polytechnique de Montréal: Accomplishments in P&P Process Simulation and Optimization", In Final Report of EU Cost E-36 project (2008).
- (8) Bakhtiari, B., **E. Mateos-Espejel**, R. Legros & J. Paris, "Absorption Heat Pumps in the P&P Industry, Part III: Feasibility study of Integration in the Kraft Process", PUR 928 (2007).

(9) Mateos-Espejel, E., L.-M. Pereira, M. Marinova & J. Paris, "Energy and Water in the Pulp an Paper Industry: the two Solitudes", PUR 926 (2007).