DEVELOPMENT OF A METHODOLOGY
TO OPTIMIZE LOW CONSISTENCY REFINING OF MECHANICAL PULP

by

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ABSTRACT

In this dissertation we present a novel two-stage procedure to relate low consistency (LC) refiner operating conditions to changes in fibre morphology. To do so, a large database of operating conditions and resulting pulp properties were collected over a range of both pilot and industrial LC refiners operating with mechanical pulps. In total eight different Andritz TwinFlo™ were sampled over a three year period in both North America and Scandinavia.

The two-stage methodology is based upon a classical dimensional analysis in which a reduced parameter space is related to each other through the use of statistical modelling. In the first stage we demonstrate a relationship between net power and operating parameters such as gap, rotational speed, diameter, plate pattern and consistency of the fibre suspension. For all refiners tested the model indicates that the net power increases nearly linearly with the inverse of gap size. In this portion of the analysis we found statistically significant relationships between operating conditions and suspension properties such as change in fibre length and Canadian Standard Freeness, an industrial standard related to pulp dewatering.

In the second stage of this methodology, we build upon the work of Forgacs [1] and demonstrate that most paper properties, e.g. the mechanical strength, are related primarily to fibre length and freeness; over 80% of all variation in the data can be attributed to these two parameters. With this novel framework, in conjunction with the statistical models, we demonstrate that an optimum operating condition exist to maximize strength, and demonstrate the sensitivity of this relationship using a number of different type pulps.

In the second portion of the thesis, we further develop a novel mechanical pulping process in which multiple stages of LC refining replace the second stage HC refining in a conventional TMP process. This
work is motivated from the need to reduce electrical energy consumption to produce mechanical pulp. Using the two-stage methodology developed in the first portion of the thesis, we demonstrate under pilot plant conditions an energy savings of over 20% in comparison to a conventional TMP process to generate mechanical pulp of equal quality.
Preface

Versions of the data presented in this dissertation have been published:


These publications were created in conjunction with my supervisors Professors Olson and Martinez. I was responsible for all aspects of the work which includes, but not limited to, developing the experimental matrix, supervising both pilot and mill trial execution, analyzing the experimental data, and the development of the statistical models.
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# LIST OF SYMBOLS

- $b$: Bar width [mm]
- $g$: Groove width [mm]
- $gd$: Groove depth [mm]
- $\theta$: Sector angle ['°]
- $\phi$: Bar angle ['°]
- $BEL$: Bar Edge Length [km/rev.]
- $n_r$: Number of bars on the rotor refiner plate []
- $n_s$: Number of bars on the stator refiner plate []
- $R_1$: Inner radius of the refiner plate [m]
- $R_2$: Outer radius of the refiner plate [m]
- $NSE$: Net Specific Energy [kWh/ton]
- $P_{total}$: Refiner total power [W]
- $P_{no-load}$: Refiner no-load power [W]
- $C$: Consistency [%]
- $\dot{m}$: Mass flow rate [kg/s]
- $FL$: Fibre length measured as the length weighted average fibre length [mm]
\( l \) Length of a measured fibre [mm]

\( n \) Number of measure fibre lengths []

\( SEL \) Specific Edge Load [J/m]

\( \omega \) Refiner rotational speed [1/s]

\( D \) Refiner diameter [m]

\( p_{in} \) Refiner inlet pressure [Pa]

\( p_{out} \) Refiner outlet pressure [Pa]

\( RPM \) Revolutions per minute [rev./min.]

\( P_{net} \) Refiner net power [W]

\( \rho \) Density [kg/m\(^3\)]

\( G \) Refiner plate gap [mm]

\( h \) Coefficient for decrease in fibre length []

\( k \) Coefficient for freeness drop []
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DEDICATION

To my parents, Markku and Tarja. Throughout my entire life you have been a source of encouragement and inspiration. Without your guidance and love I would not be the man I am.

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1. INTRODUCTION

Thermo mechanical pulping (TMP) is a commonly used method to convert wood chips into high-quality papermaking fibres. The process involves multiple stages of refining which progressively comminutes chips into individual fibres. Refiners modify both physical and chemical properties of the fibre cell wall which enables them to bond together more effectively in the paper sheet. This enhances the resulting paper properties.

Although it is well established that refining dramatically enhances paper properties, the TMP process overall is very inefficient in terms of the energy consumed in comparison to the required energy to change the morphology of the fibre surface; theoretical estimates indicate efficiency even less that 1% [2]. To highlight this, in British Columbia Canada, seven mechanical pulping facilities consume approximately 10% of the total electrical energy generated in the province. This vast inefficiency has economic implications as well. Over the last number of years, the rising cost of electrical energy has eroded the potential capital and operating cost advantages that the TMP process has over other pulping processes. The future of the mechanical pulping industry therefore depends on the mills ability to dramatically improve the overall efficiency of this process.

Approximately 80% of the total energy in the TMP process is consumed by HC refiners powered by 10-30 MW motors. It is widely known that the literature on this particular aspect of the TMP process, i.e. elevated or high consistency refining, is substantial. The depth of knowledge in this area is so great, that a significant research effort may be required to achieve marginal gains in energy savings. To help reduce energy consumption, many mechanical pulp mills have displaced the use of HC refiners with more energy efficient refining processes at lower consistencies. Our understanding of mechanical pulp response to LC refining is minimal; it is from this starting point that this dissertation is motivated.
In this dissertation a novel two-stage methodology to relate LC refiner operating conditions to changes in mechanical pulp quality is presented. The proposed methodology provides guidelines for optimal mechanical pulp LC refining. In addition, an improved TMP process maximizing the use of LC refining is developed. The improved TMP process uses a single stage of HC refining to comminute wood chips to individual fibres, followed by multiple stages of optimized LC refining.

The dissertation begins with an overview of the TMP process with a focus on the design and operations of a TwinFlo™ LC refiner. This is presented in Chapter 2. Following this, a review of the relevant LC refining literature is presented in Chapter 3. The review provides the background information required to understand the objectives for this research, which is presented in Chapter 4. Chapter 5 proposes a framework to analyze, and optimize LC refiners by studying a range of refiners and operating conditions. Finally the improved TMP process is presented in Chapter 6. The two last chapters, Chapters 7 and 8, give a summary of the contributions as well as recommendations for future research.
2. BACKGROUND: THERMO MECHANICAL PULPING (TMP)

In this section, the process of producing thermo mechanical pulp (TMP) is briefly reviewed as well as some of the key operating and characterization methods for low consistency refiners. The intended purpose of this chapter is to familiarize the reader with some of the commonly used industrial terms, such as "bar edge length" and "no-load power"; these terms are used extensively in this dissertation.

Refiners are mechanical devices used to comminute wood chips into individual fibres. They are rotary machines in which the wood fibre, in whatever form, is passed through the annular gap between two closely spaced discs; one disc rotates, i.e. the rotor, while the other one is stationary, i.e. the stator. The spacing between the rotor and the stator, referred to as the gap, is typically of the order of a few fibre widths. Wood chips, and subsequently the papermaking fibres, are refined by the grinding action of the roughened topography surfaces of the rotor and stator plates. These roughness elements are usually repeating units of bars and grooves formed into patterns which also allow for transport of the suspension; the design of the bar pattern on each disc is particular to the type of refining action required. In the TMP process the comminution of wood chips to individual fibres and the subsequent pulp quality development is almost exclusively performed through this mechanical attrition.

The TMP process contains a number of different refining treatments. The type of refining treatment is typically categorized by the concentration of the feed suspension. The industrial term which is related to the scientifically-accepted definition for concentration is "consistency", and is defined as the ratio of the mass of fibres to that of the suspension. Under dilute conditions concentration and consistency can be used interchangeably; further details of this are given by the TAPPI standard T240.
A conventional TMP process is presented in Figure 1a. Pre-screened and washed wood chips are heated with steam, and fed into the primary HC refiner at a consistency of approximately 20-40%. Here, the wood chips are comminuted into individual fibres by the forces imposed by the bars of the opposing rotor and stator plates. Following this, steam is recovered, and the pulp is subjected to a second HC refining treatment to further enhance the changes in fibre morphology. Further steam is recovered, and the suspension is diluted to a consistency of approximately 3-4% in the latency tank. Refining is conducted at this lower consistency in the tertiary refiner. The energy consumption for each unit operation in a conventional TMP process is shown in Figure 1b. As mentioned previously, the HC refiners
consume most of the energy in this process (60% + 17.4% = 77.4%), and only a small fraction of the total energy is used by the LC refiners.

2.1 Low consistency disc refiner

There are some profound differences with regards to the fluid mechanics and the behaviour of these suspensions when processed at high (HC) or low consistencies (LC). HC refining is a heterogeneous three-phase system of wood fibres, water, and steam. This heterogeneous three-phase mixture flows radially, both outward and inward, between the rotating plates, and the motive power to move pulp through the refiner comes from feed screws. Details of this are given in [4]-[13] and the references within.

At low consistency the pulp suspension acts as an incompressible fluid, which may be pumped through the refiner using an external pump. This mixture is more homogeneous and consequently the refining treatment more uniform as demonstrated by the smaller, more uniform gap between the plates, and the more stable refiner power consumption. The precise physical reason for the increased efficiency of LC refining is still unknown, although the uniformity of treatment may be a possible origin. During proper operations, LC refiners do not generate steam, and the fibres remain surrounded by sufficient water during the entire refining action. Another benefit of LC refining, related to the above, is that the intensity of the treatment and pulp throughput can be decoupled, allowing them to be independently controlled and optimized.

Various types of LC refiners can be found in modern pulp and paper processes, and each refiner type has its own characteristics. This dissertation concentrates on studying the Andritz TwinFlo™ LC refiner design, as this is the most commonly found LC refiner design in British Columbia pulp and paper mills.
TwinFlo™ refiners are rotary devices with one rotor and two stators. As shown in Figure 2, they consist of the following key parts: motor, drive train (including a gear box and shaft), floating rotor, and two stators (labelled far-side and drive-side). The size of the refiner plates is determined nominally by the size of the housing and the motor. Some flexibility exists as slightly over- or undersized diameter plates may be used, if they fit the refiner housing.

Most LC refiners operate at a fixed rotational speed, as variable frequency drive trains are not commonly found in industrial refiners. Most applications utilize a gear box between the motor and drive shaft to set the refiner rotational speed. The rotor is attached to the drive shaft, but is not axially constrained. This allows the rotor to move freely between the stator discs, and is therefore called a floating rotor. The pulp feed to a TwinFlo™ refiner is conventionally performed by a single inlet feeding into the drive-side refining zone. The floating rotor is equipped with openings on its inner diameter to

*Figure 2 Illustration of a TwinFlo™ low consistency refiner cross section, red sections represent refiner plates.*
allow pulp flow through the rotor to the far-side refining zone. Pulp discharge from the refiner occurs separately from each refining zone, and is combined into a single line shortly after the refiner.

The gap size between the two refining zones in a TwinFlo™ refiner is controlled by displacing the far-side stator usually with a stepper motor and screw combination. The change in the cumulative gap size between the rotor and stator plates in both refining zones effects the total power required to operate the refiner; the motor load generally increases monotonically with decreasing gap. The floating rotor then moves between the two stators according to the applied force on each refining side. The pressure at each refining zone can be altered by restricting the discharge flow rate from the zone.

One important aspects of operating the refiner is the correct choice of plate design. Refiner plates used in the industry come in various different designs according to the pulping process. Although the construction of the refiner itself does not change between mechanical and chemical pulp refining, the refiner plate designs vary significantly. Figure 3a and 3b show a simplified illustration of a straight and spiral bar pattern refiner plate, both common designs used in pulp refining. The refiner plate design is characterized by bar width \( b \), groove width \( g \), groove depth \( gd \), sector angle \( \theta \), and bar angle \( \phi \), Figure 3a) and c).
The straight bar design shown in Figure 3a has a number of sectors composed of a series of parallel bars machined at a constant angle, measured relative to the radial direction. The spiral bar design in Figure 3b has bars which are in the shape of concentric spirals; the advantage of such a design is the constant bar crossing angle between opposing plates.

Plate designs are typically characterized by the length of intersecting edges between the opposing plates, and is typically termed as the “bar edge length” (BEL). BEL is a standardized measure in the industry and is estimated using TAPPI standard TIP 0508-05 (1994):

$$BEL = \int_{R_1}^{R_2} \frac{n_r(r) \cdot n_s(r)}{\cos \phi} \, dr$$

Eq.(1)

where $n_r(r)$ and $n_s(r)$ are the number of bars on the rotor and stator plate at a given radius, $R_1$ and $R_2$ are the inner and outer radii of the refiner plates, respectively.

Figure 3 Illustrations of a) straight, b) spiral bar refiner plate design, and c) plate cross section
To approximate this integral, the number of bars on each plate can be estimated crudely by setting:

\[
n(r) = \frac{2\pi r}{b + g}
\]

Eq.(2)

With this, Equation 1 can be integrated directly to yield:

\[
BEL = \frac{(2\pi)^2}{\cos \phi} \left( \frac{R_2^3 - R_1^3}{3(b + g)^2} \right)
\]

Eq.(3)

At this point we turn our attention to define an operating parameter used through the dissertation, i.e. the no-load power. No-load power refers to the power used by the refiner for purposes other than changes in fibre morphology. The LC refiner no-load power has been estimated to be 20-35% of total refiner motor power, and is categorized into [14]:

- electrical-to-drive energy converting losses
- losses due to mechanical friction in the bearings
- hydraulic losses through turbulences and fibre friction
- pumping losses due to the fibre suspension flow

There is no generally accepted standard, or methodology to estimate no-load power. In this dissertation the following definition is used: the no-load power is the power required to operate the refiner at its desired speed, consistency, and flow rate at a gap size such that there is no changes in the fibre morphology. With this, we can now characterize the net power to cause changes in fibre morphology as the difference between the total measured and no-load power.
Although seemingly simple, the number of control and response variables involved in the LC refining process indicates a complex system. Specifically, the complex physical interaction between the refiner plate and fibre treatment has long been a source of debate, and it is yet to be understood.

The different variables found in the LC refining process can be divided into six categories: primary variables, secondary variables, passive variables, process disturbances, output variables, and response variables. This is outlined in Figure 4.

Motor power, pulp flow rate and recirculation are categorized as primary variables, as they are used to control the refiner, and can be altered during the refining process. Secondary variables include: no-load power, net power, gap size, changes in temperature and pressure. These variables are either measured, or calculated using the primary variables, and are therefore indirectly used to control the refiner. One of the key variables for controlling the changes in fibre morphology is the net specific energy (NSE), defined as the ratio of the net power to the mass flow rate of fibre [15].
As this definition is used extensively throughout this dissertation, we formally define this as:

\[
NSE = \frac{P_{\text{total}} - P_{\text{no-load}}}{C \cdot \dot{m}} \tag{4}
\]

where \( C \) is consistency of the pulp, and \( \dot{m} \) is the mass flow rate of the pulp suspension.

The passive variables are rotational speed, plate design, and diameter, which remain constant during refining action, and can only be altered when the refiner is not in operation. Process disturbances have a significant effect on the operations of the refiner, but cannot be controlled with the LC refiner as they originate from previous process stages, such as HC refining and latency removal. LC refining output variables are defined as the changes in fibre properties, including properties such as fibre length and freeness. The response variables represent the pulp properties, here final paper properties made from the pulp produced, measured as handsheet properties.

### 2.2 Pulp properties

Throughout this dissertation we measure a number of pulp properties which are used to characterize the refining result. A number of these reported properties are unique to the pulp and paper industry, and form a language common to the technologist. In some cases, it is difficult, if not impossible to relate these industry standards to more commonly defined terms found in the scientific literature. We do not attempt to do so in this dissertation, but simply report the industrial standard test methods and define each parameter below for clarity.

In this dissertation, the properties of freeness, tensile index, tear index, bulk and fibre length are considered, as they are amongst the most commonly used properties to describe the quality of mechanical pulp. We recognize that LC refining alters the optical properties of mechanical pulp, but do not comment on this.
1. **Canadian Standard Freeness (CSF) [ml]** is a measure of the volume of water collected from a pulp suspension drained from one exit-nozzle in a specialized dewatering cell. This measurement technique is specific to the industry, and is difficult to relate to concepts such as permeability. It is widely accepted in the pulp and paper industry, where “higher freeness” implies a pulp which is easier to drain. The standard procedure of measuring pulp drainage is laid out in standard TAPPI T227.

2. The **tensile index [Nm/g]** is the ratio of the tensile strength per unit width [N/m] of a paper sheet to its areal density, i.e. basis weight [g/m²]. The tensile index is a measure of the ultimate strength of paper. It is normalized to its areal density, opposed to its thickness, as the thickness of the paper is highly variable. In this case, the roughness elements of paper are the same order of magnitude as its average thickness. The standard method for this measurement is explained in TAPPI T494.

3. **Tear index [mNm²/g]** is calculated similarly to the tensile index by dividing the measured tear strength [mN] of the paper sheet normalized by its basis weight [g/m²], TAPPI standard T414. Higher paper tear strength indicates greater resistant to the propagation of a tear.

4. **Bulk [cm³/g]** indicates the inverse of sheet density, calculated from caliper, i.e. thickness [mm], and basis weight [g/m²], TAPPI standard T500. Bulk, or paper density, is related to the resulting paper quality, and higher bulk is desired for absorbent papers.
5. Fibre length [mm] is one of the most important parameters, and various automated methods exist to rapidly measure a large number of fibres. Most automated methods produce a frequency distribution of the fibre lengths measured. Typically fibre lengths range from 0.1-4 mm. In this dissertation, we report an average value of the fibre length (FL) according to the length weighted average fibre length:

\[ FL = \frac{\sum l^2 \cdot n}{\sum l \cdot n} \]  \hspace{1cm} \text{Eq.(5)}

2.3 Summary

In this section we introduced a number of concepts to aid the reader in understanding the balance of the dissertation. In the first part we introduced the thermo mechanical pulping process, and reviewed the major unit operations. Here we find that wood chip comminution to individual fibres and subsequent fibre morphology development is achieved through a number of refining steps. The majority of this traditional process occurs at high consistencies (20-40%), while the final steps are at low consistency (3-5%). We then focussed our efforts on defining the parts of the unit operation which will be studied in detail in this dissertation – the low consistency refiner. Finally, we report on the typical test methods to characterize the refining effect on fibre morphology.
3. LITERATURE REVIEW

In this section, we present a concise survey of both the changes in fibre morphology and the various attempts to create a theory to understand the fibre refining action. It must be stated up-front that although the LC refining literature is vast, the focus of the present dissertation is on the behaviour of mechanical pulps in LC refiners. For work within the field of chemical pulping, the reader is referred to either of the excellent reviews by Ebeling (1980) or Page (1989), and the references contained therein [16][17]. However, the literature in the mechanical pulping process is not as complete.

In this section we present a partial review of material obtained from the vast chemical pulp LC refining literature, which we feel is pertinent to understand the behaviour with mechanical pulps. As such we begin the review by examining the anatomy of a fibre with the hope of defining how macroscopic properties, such as flexibility, are related to the cell wall structure. Following this we examine a number of mechanistic or statistical approaches to characterize the refining effect. We do so as one of the goals of the current dissertation is to develop a methodology to correlate the refining effect to changes in the fibre morphology. It is instructive to first examine the approaches given in the LC refining literature.

3.1 Fibre morphology

The morphology of wood fibres, as well as their chemical and physical characteristics depends on both species and growing conditions. The cell wall of a wood fibre consists of concentric layers with different functions, physical structure and chemical composition. A typical model of a fibre cell wall can be seen in Figure 5.
The middle lamella contains much of the lignin holding the fibrous wood fibres together, and can be identified as a clear transition region between fibres; though most of the lignin is found in the fibre cell wall. The middle lamella surrounds the primary wall, which has crossing fibrils layered on top of each other. The next layer is the secondary wall consisting of the different S-layers; outer, middle and inner layer. The first layer beneath the primary wall is the S1 layer, with fibril arranged in several counter running thin layers. The middle layer, S2, is the thickest layer containing approximately 80% of the entire cell wall thickness, and fibrils in this layer are in parallel with a steep angle forming a helical structure. The inner most layer surrounding the lumen, open area inside the fibre, is the S3 layer, with a warty surface and fibrils less strictly arranged as in the S1 layer [18]. The final fibril angle of any cell-wall layer depends on both wood species and growth period, which all play an important role in fibre collapse in paper making [19].

Fibre fibrillation can be divided into external, internal and molecular fibrillation. External fibrillation peels off fibre outer layers of the fibre cell wall, whereas internal fibrillation consists of splitting the coaxial structure of the inner cell wall, allowing for fibre swelling. Molecular fibrillation dissolves the polymeric structure of the matrix components of the fibre cell wall, which some researchers have claimed to be the most important form of fibrillation [20][21].
In refining the creation of new fibre particles can be divided into two subclasses of fibre cutting and peeling. Fibre cutting is a deleterious effect of refining, although the creation of fines, small pieces of fibre, has a positive effect on certain paper properties. In peeling, parts of the fibre cell wall are pulled off which reduces cell wall thickness and enhances fibre collapse. These small pieces also aid fibre bonding by filling the gaps between fibres during sheet forming. Further the fines increase the optical properties of paper made from mechanical pulp.

The creation of structural changes to the fibre cell wall is not as clearly defined as fibre fibrillation and breakage. Structural changes can be divided into the generation of radial compression zones, and the flexing of the fibre. Radial compressions collapse the lumen, the cross section bound by fibre cell wall, which enhances paper smoothness and sheet uniformity in paper making [22]. Increased fibre flexibility increases fibre bonding properties, hence increasing final paper properties.

These refining effects correlate with each other. As the thickness of the fibre cell wall decreases with external fibrillation, fibres collapse more readily. The ability for the fibres to bond with each other in a paper sheet is influenced by its flexibility and degree of fibrillation. The amount of small particles, i.e. fines, created has an effect on the resulting pulp drainage and optical properties.

In late 1990's Mohlin studied fibre development during mechanical pulping, [23]. She found that changes in fibre properties did not occur uniformly for all fibres, as thin walled spring wood fibres were more prone to the unravelling of the S2 layer compared to the thick walled summer wood fibres. The various fibre fractions in mechanical pulp correlate to different paper properties. Mohlin stated that: "Mechanical pulp with long and slender fibres with high bonding potential is preferred for the best possible combination of runnability, surface smoothness, surface strength, and surface dimensional stability. Optical properties are very much influenced by the specific surface of the pulp, not only from the fines fraction, but also from other fractions. Quality of TMP is mainly determined by the particle size distribution and by specific surface".
3.2 Characterizing the beating action

In the previous section, we presented information regarding the physical changes in the fibre morphology during refining. A number of authors have attempted to build a framework, based on these microscopic studies, to understand the macroscopic or bulk changes to the suspension during passage through the refiner. The framework is built upon the assumption that the morphological changes in the fibre cell wall occur through a fatigue type mechanism. Here, individual fibres undergo cyclic stresses during repeated bar crossings in the refiner [24][25].

Several models have been developed for chemical pulps to describe the refining action using two-parameters which capture the essence of a fatigue-type process, i.e. by the number (N) and intensity (I) of impact. When combined, the number of impacts times the intensity of impact represents the total energy expended on the pulp (per unit mass). Most of these models have been created, and validated by using chemical pulps, but regardless of the fundamental differences between mechanical and chemical pulps, it is important to understand the way these models characterize the refining action, and to identify their shortcomings.

In perhaps the most widely accepted model for understanding the intensity of treatment, Wultsch and Flucher defined the "Specific Edge Load" (SEL) [26]. In this work the authors assumed that most of the energy dissipated onto the network occurs between the intersecting bars. As a result, they advanced an equation where they normalize the net energy applied to the total length of bar edges on the refiner plate design (BEL):

\[
SEL \left[ \frac{J}{m} \right] = \frac{P_{total} - P_{no\text{-}load}}{BEL \cdot \omega} \quad Eq.(6)
\]

\(SEL\) represents the most widely accepted parameter for intensity, and was widely adopted after the work of Brecht and Siewert [27]. Since this classic work, a number of other research groups have
advanced models attempting to address issues with this definition of intensity. Lewis and Danforth published a semi-empirical model to account for plate geometry in a more rigorous manner [28]. Lumiainen questioned the assumption regarding the refining effect over the bar edge, and extended his results to the bar area [29][30]. Meltzer and Siewert introduced their Modified Edge Load theory, which accounted for the number of bar crossings in the estimate of surface area [31].

Kerekes advanced a rigorous methodology to estimate both the number of impacts and the intensity of impacts and called this approach the C-Factor [32]. He demonstrated that the refining effect could be correlated to these two parameters; refining intensity calculated by the C-Factor is shown to better correlate with pulp quality development then intensity calculated by the specific edge load theory.

In perhaps the most serious criticism of the two parameters approach Howard et al. [33] used a statistical approach, i.e. principal component analysis, and showed that 3 parameters accounted for 94% of the total variance in the data collected from various refiners and different chemical pulps. Similarly in 2006, El-Sharkawy et al. applied factor analysis in an attempt to control chemical pulp refining [34]. Recent results by Gooden et. al. [35], indicate that fibre redistribution after the imposition of stress is an important mechanistic step in achieving uniform refining results. We interpret these results to indicate that the refining event is a more complicated process than simply a fatigue-type, and as a result, limits the utility of a process description by means of only two parameters.

In related work, a number of authors have considered the refiner to behave as a simple piece of turbo-machinery, and advanced empirical relationships to relate operating conditions to the net power applied to the pulp.
Herbert and Marsh [36] applied an integral energy balance, and demonstrate that energy is consumed through disk friction, work on the suspension and pumping losses, and advanced an equation of the form:

\[ P_{total} = K_d \omega^3 \left( D_0^5 - \frac{2}{3} D_i^5 \right) + K_e \omega D_i \left( D_0^2 - D_i^2 \right) + K_p \dot{m}_{pump} \omega^2 D_0^2 \]  

Eq.(7)

where \( K_d \) is an empirical constant which accounts for losses due to flow over rough plate surfaces; \( K_e \) is a constant relating the energy transferred from the refiner plates to the fibre suspension; and \( K_p \) is a constant which considers the energy consumption in pumping the fluid through the refiner.

In other work, experimental measurements of Goncharov [37], and Martinez et. al. [38] confirmed that a large portion of the shear force applied to the fibres occurs when the leading edges of the bar intersect. This force based approach is based on the hypothesis that: "Energy reflects the total work done on fibres, but this does not describe the forces which strain fibres" [39]. Various researchers continued to study the refining action with the force based approach, yet we see no feasible models for fibre development used in practice [40]-[42].

Recently Kerekes [43] has combined the two parameter approach of refining intensity and energy with the force based approach: "Force is a key missing factor in current approaches to quantify refining action". He characterizes the refining action as "abrasion"; a combination of both force (acting on the fibre) and sliding (relative movement between bar and fibre surface).

Finally, the plate gap size in LC refining has been shown to be an important variable correlating with other refiner operating variables, especially motor power. Mohlin [44] has demonstrated that plate gap is inversely proportional to refiner power; similar to the findings of May et. al. [45] for HC refiners. Mohlin concluded that: "The plate gap and the power input have a large effect on the refining result and that they should be looked at as the primary variables in refining instead of measures of refining
intensity”. For her studies she used unbleached kraft pulp, and only presented changes in pulp properties for water retentions value and fibre length. Batchelor et. al. [46] have studied the power and gap relationship with softwood chemical pulp and a conical refiner, and Murton et. al. [47] have found gap size to correlate with pulp quality changes in HC refining.

3.3 Summary of the literature

To summarize the relevant literature in this section, we find that refining is the process in which the morphology of the papermaking fibre is modified by the imposition of stress, applied in a cyclic manner, to create more flexible fibres with increased surface area for better bonding. The literature in the area of LC refining of mechanical pulps is small in comparison to that available for LC refining of chemical pulps. What we find for chemical pulps is that there is no generally accepted mechanism by which energy is transferred from the refiner surface to the papermaking fibre. A large number of authors have built mechanistic understandings by considering the refining event to be somewhat like a classic fatigue type process. This framework has had limited success in relating operating conditions to final paper properties. There are a number of other key works which highlight the importance of other parameters such as gap size; parameters not considered in the fatigue type approach. The lack of ability to predict the operation of the refiner, or even to have a universally accepted framework for analysing the refining action, severely limits both the design engineers and mill personnel in operating these devices. It is from this point that our research is motivated.
4. RESEARCH OBJECTIVES

The relevant literature shows the complexity of LC refiners, as well as the importance of the proper refiner operating conditions for maximum pulp quality development. Various refining theories and models have been created to characterize LC refiners, and the limitations of the previous approaches lay in their lack of correlations to pulp quality development. As the majority of these models have been created for chemical pulps, their accuracy on refining mechanical pulp remains unknown.

As a result the specific objectives of this research are:

- To develop a framework to relate the LC refining action to the changes in fibre morphology
  - To validate this framework over a wide range of operating conditions for a number of different size refiners
- To advance guidelines for optimal LC refiner operation
- To demonstrate energy savings by replacing HC refining with LC refining in the TMP process
5. FRAMEWORK TO ANALYZE LC REFINING ACTION

In this section, a novel framework to analyze the relationship between LC refiner operating conditions and mechanical pulp properties is presented. This relationship is given in a two-step methodology. In the first step we relate operating conditions to changes in fibre length and freeness; we approach this problem using a traditional dimensional analysis. The models are built through a statistical analysis; a functional relationship is sought for the changes in, say freeness, in terms of operating parameters. In the second step, we show that most paper properties, made from mechanical pulps, are a function of fibre length and freeness. This second step is not new. We revive, and build on, the work of Forgacs who demonstrated this nearly fifty years ago [1].

The purpose of this dissertation is not to characterize the refining action, but to study correlations in the experimental data collected. From the correlations found we are able to identify key operating variables effecting pulp quality development; approach selected allows us to implement our findings directly to existing refining systems.

One of the important steps in completing this task is to collect data over the widest range of conditions possible. Towards this end, a large survey of LC refiners in the province of British Columbia, as well as in the United States and Scandinavia, in which operating conditions and changes in pulp properties were collected. This database was collected over a three year period and subsequently analyzed. In this section, we begin by outlining the refiners used in this survey. Following this, we report on the first stage in this framework, i.e. relating operating conditions to fibre length and pulp freeness, and then build upon the work of Forgacs in the second step of this framework.
5.1 Experimental

Data for the framework to analyse LC refiners was collected from eight different refiners, one at pilot scale, seven located in pulp and paper mills. The used experimental protocol varies greatly between pilot and mill trials, and will be described next.

5.1.1 Pilot trials

Pilot trials were designed to determine the effect of LC refiner operating conditions on mechanical pulp quality. A range of rotational speeds, motor powers, mass flow rates and plate geometries were studied for three different freeness pulps.

The three freeness pulps studied had an initial freeness of 120ml, 350ml, and 550ml. The 120ml freeness pulp was selected as it is a fair representation of feed pulp freeness to a tertiary refiner in a conventional TMP process. The two higher freeness pulps were selected to simulate a TMP process with reduced secondary HC refiner energy, resulting in a higher feed freeness to the tertiary stage LC refiner. For the selected feed pulps it is possible to increase conventional tertiary stage LC refining energy, and to further study the potential TMP energy savings.

Dried bales of market TMP pulp, made from a mix of spruce, pine and fir (SPF) with a low chemical chip pre-treatment from interior British Columbia, were shipped to the Andritz pilot plant in Springfield, Ohio. The dried bales were re-pulped at the beginning of each trial, resulting in minor variations in feed pulp quality between trials. The consistency was held constant at approximate 4% for all trials, as was initial pulp temperature at approximate 65°C. These values were selected as they are similar to the conditions found in industry.
Figure 6 shows an illustration of the used pilot LC refining loop with a 0.56m (22") Andritz TwinFlo™ refiner. The pulp was passed through the refiner in batches from tank-to-tank, 7 passes for each trial. With each pass, the cumulative net specific energy (NSE), net energy per unit mass of fibre, was increased with constant increments shown in TABLE 1. All variables shown in Figure 6 were recorded, in addition to measured pulp properties. Pulp samples were collected from the tank after each pass through the refiner to minimize variation in the measured pulp properties. During multiple pass refining, the temperature of the pulp increased 15 to 20 °C.

The refiner net power was varied through changes in the gap between plates. Gap size was estimated by recording the movement of the far side refiner housing with an external LVDT sensor, and dividing the values by two, as there are two refining zones. As shown earlier for the LC refiner construction, the assumption made for an even gap size between the two refining zones is invalid because of the floating rotor. Regardless of the inaccurate gap measurement, this methodology does provide estimates for the plate gap. The gap was measured continuously during the refining of the entire pulp volume from one tank to another, and the reported gap sizes are an average for each pass.
Two Andritz Durametal spiral plate designs were used, Figure 7. Both plate designs have the same constant bar crossing angle of 24°, and bar height of 6.35mm. The 22TA101/102 plate has a higher BEL of 14.65 km/rev with a bar width of 1.65 mm, groove width changing from 2.29 mm to 2.54 mm along the radius. The 22TA103/104 plate has a BEL of 10.29 km/rev with the same bar width as the first plate, but a greater groove width increasing from 3.05 mm to 3.30 mm due to fewer bars per plate. These plates were selected for their high bar edge lengths and suitability for refining mechanical pulps.

TABLE 1 shows the average refiner operating conditions for each trial, with the refining intensity values calculated according to the SEL theory. These operating conditions were kept constant for seven passes, increasing the cumulative NSE applied with a constant increment each pass. The refiner operating conditions were selected in a manner which would span the full range of each variable. With this experimental design, the effect of selected variables could be studied separately.
**TABLE 1 Detailed pilot LC refiner operating conditions for market TMP**

<table>
<thead>
<tr>
<th>Trial</th>
<th>Feed</th>
<th>BEL</th>
<th>RPM</th>
<th>NSE per pass</th>
<th>Flow rate (pulp)</th>
<th>SEL Intensity</th>
<th>$P_{\text{net}}$</th>
<th>$P_{\text{no-load}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>[ml]</td>
<td>[km/rev.]</td>
<td>[rev./min.]</td>
<td>[kWh/ton]</td>
<td>[l/min.]</td>
<td>[J/m]</td>
<td>[kW]</td>
<td>[kW]</td>
</tr>
<tr>
<td>A</td>
<td>116</td>
<td>10.30</td>
<td>1200</td>
<td>61</td>
<td>431</td>
<td>0.31</td>
<td>63</td>
<td>189</td>
</tr>
<tr>
<td>B</td>
<td>115</td>
<td>10.30</td>
<td>1138</td>
<td>68</td>
<td>371</td>
<td>0.31</td>
<td>61</td>
<td>163</td>
</tr>
<tr>
<td>C</td>
<td>108</td>
<td>10.30</td>
<td>800</td>
<td>63</td>
<td>540</td>
<td>0.60</td>
<td>83</td>
<td>61</td>
</tr>
<tr>
<td>D</td>
<td>120</td>
<td>10.30</td>
<td>949</td>
<td>64</td>
<td>645</td>
<td>0.62</td>
<td>100</td>
<td>99</td>
</tr>
<tr>
<td>E</td>
<td>120</td>
<td>14.65</td>
<td>1138</td>
<td>81</td>
<td>373</td>
<td>0.26</td>
<td>73</td>
<td>144</td>
</tr>
<tr>
<td>F</td>
<td>120</td>
<td>14.65</td>
<td>800</td>
<td>71</td>
<td>373</td>
<td>0.33</td>
<td>64</td>
<td>54</td>
</tr>
<tr>
<td>G</td>
<td>115</td>
<td>14.65</td>
<td>1200</td>
<td>77</td>
<td>569</td>
<td>0.35</td>
<td>104</td>
<td>167</td>
</tr>
<tr>
<td>H</td>
<td>120</td>
<td>14.65</td>
<td>800</td>
<td>41</td>
<td>372</td>
<td>0.18</td>
<td>36</td>
<td>54</td>
</tr>
<tr>
<td>I</td>
<td>118</td>
<td>14.65</td>
<td>1200</td>
<td>46</td>
<td>567</td>
<td>0.22</td>
<td>64</td>
<td>167</td>
</tr>
<tr>
<td>J</td>
<td>131</td>
<td>14.65</td>
<td>1200</td>
<td>60</td>
<td>403</td>
<td>0.20</td>
<td>59</td>
<td>167</td>
</tr>
<tr>
<td>C2</td>
<td>387</td>
<td>10.30</td>
<td>1200</td>
<td>59</td>
<td>402</td>
<td>0.28</td>
<td>58</td>
<td>189</td>
</tr>
<tr>
<td>D2</td>
<td>362</td>
<td>10.30</td>
<td>1000</td>
<td>63</td>
<td>403</td>
<td>0.36</td>
<td>62</td>
<td>114</td>
</tr>
<tr>
<td>E2</td>
<td>375</td>
<td>14.65</td>
<td>1200</td>
<td>59</td>
<td>403</td>
<td>0.20</td>
<td>58</td>
<td>167</td>
</tr>
<tr>
<td>F2</td>
<td>383</td>
<td>14.65</td>
<td>1100</td>
<td>60</td>
<td>709</td>
<td>0.39</td>
<td>105</td>
<td>131</td>
</tr>
<tr>
<td>A2</td>
<td>540</td>
<td>10.30</td>
<td>1200</td>
<td>59</td>
<td>401</td>
<td>0.28</td>
<td>57</td>
<td>189</td>
</tr>
<tr>
<td>B2</td>
<td>573</td>
<td>10.30</td>
<td>1000</td>
<td>64</td>
<td>403</td>
<td>0.36</td>
<td>62</td>
<td>114</td>
</tr>
<tr>
<td>G2</td>
<td>549</td>
<td>14.65</td>
<td>1200</td>
<td>60</td>
<td>403</td>
<td>0.19</td>
<td>57</td>
<td>167</td>
</tr>
<tr>
<td>H2</td>
<td>547</td>
<td>14.65</td>
<td>1100</td>
<td>61</td>
<td>714</td>
<td>0.38</td>
<td>102</td>
<td>131</td>
</tr>
</tbody>
</table>

The no-load power, $P_{\text{no-load}}$, measurements were done running the refiner with a constant wide open gap size of 2.54 mm (0.1”). The power required to operate the refiner was measured for both 4% consistency pulp and water and the two plate designs used in the pilot trials.
Figure 8 No-load power measurements done with water and pulp for both pilot trial plate designs

Figure 8 shows the collected no-load data for flow rates from 230 to 950 litre/min. A strong correlation can be seen for rotational speed, and a lesser effect for plate design; no correlation for changing flow rate. No-load power can be seen to increases slightly for plate 22TA103/104 with the lower BEL of 10.30 km/rev. Interestingly similar no-load measurements were recorded for both pulp and water under similar conditions, indicating no-load power to be independent of the difference between water and pulp for the range of conditions tested. The power law trends in Figure 8 agree with the findings of Brecht for conical refiners [15].

5.1.2 Mill trials

LC refining trials conducted at pulp and paper mills are more restrictive in comparison to the pilot trials. The refiners are a part of the continuous TMP process, where little or no control is given over the LC refiner feed pulp and wood species mix. Motor power and pulp flow rate are the only operating conditions which can be altered during normal operations of the LC refiner.
The experimental protocol used to trial mill LC refiners was to run multiple power levels for a given pulp flow rate, change the flow rate, and then repeat the previous power levels. The pulp samples were collected at each power, after the operating conditions had reached steady state. The refiner operational variables were controlled and recorded by the mills Distributed Control system (DCS). Details of the conditions tested are shown in TABLE 2.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Feed Freeness</th>
<th>BEL</th>
<th>RPM</th>
<th>Diameter</th>
<th>Motor Size</th>
<th>No-load Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill A</td>
<td>80</td>
<td>97</td>
<td>509</td>
<td>1.07 (42)</td>
<td>1200</td>
<td>310</td>
</tr>
<tr>
<td>Mill B #1</td>
<td>140</td>
<td>377</td>
<td>425</td>
<td>1.40 (55)</td>
<td>2000</td>
<td>307</td>
</tr>
<tr>
<td>Mill B #2</td>
<td>140</td>
<td>486</td>
<td>425</td>
<td>1.47 (58)</td>
<td>2000</td>
<td>473</td>
</tr>
<tr>
<td>Mill C</td>
<td>245</td>
<td>368</td>
<td>425</td>
<td>1.47 (58)</td>
<td>2500</td>
<td>343</td>
</tr>
<tr>
<td>Mill D #1</td>
<td>150</td>
<td>410</td>
<td>425</td>
<td>1.32 (52)</td>
<td>2000</td>
<td>420</td>
</tr>
<tr>
<td>Mill D #2</td>
<td>160</td>
<td>320</td>
<td>425</td>
<td>1.47 (58)</td>
<td>2000</td>
<td>660</td>
</tr>
<tr>
<td>Mill D #3</td>
<td>130</td>
<td>414</td>
<td>320</td>
<td>1.83 (72)</td>
<td>5000</td>
<td>800</td>
</tr>
</tbody>
</table>

Refiner no-load values were measured for a wide open gap with pulp flowing through the refiner, similarly to the pilot trials. Some uncertainty exists for the accuracy of the measured no-load values, as each value is a single measurement, and is subject to change depending on the position of the floating rotor.
The majority of the tested mill refiners do not have active gap measurement systems in place. To estimate plate gap size, an external Linear Variable Differential Transformer (LVDT) sensor is attached to the refiner external housing with magnetic clamps, Figure 9. The sensor measures the movement of the far-side refiner housing, similarly to the method used in pilot scale. The recorded values are divided by two for the two separate refining zones of the TwinFlo™ refiner. Calibration of the sensor is done by driving the refiner plates to contact with the refiner not running. The calibration method used does not necessarily provide a true zero gap reading, as it is impossible to verify that no pulp is stuck in the gap between refiner plates. To minimize this possible error, multiple calibration points are measurement.

As the same protocol for gap size estimation is used for both pilot and mill trials, later references to gap size in this dissertation are to be considered as the estimated gap size acquired by the procedure outlined above.

Plate life varied between refiners tested, but all of the plates had been in production for long enough to diminish the increased fibre cutting seen with new plates and sharp bar edges [48].

Figure 9 LVDT sensor installation to the refiner housing with magnetic clamps to estimate refiner plate gap
5.2 From LC refiner operating conditions to changes in pulp properties

Before introducing our two step framework, we begin by analysing the results of the pilot trials in a traditional manner. Most mills relate the operation of the refiner by examining the changes in tear and tensile indices as a function of the intensity of the refining treatment. Intensity in this case is defined by Specific Edge Load, Equation 3. This is shown in Figure 10 for a range of LC refining conditions tested at pilot scale with a pulp which had an initial freeness of the 120 ml; the hatched lines represent different intensities. Under ideal refining operations, the practitioner hopes for a response of increasing tensile strength with little degradation in tear strength. What is evident in Figure 10 is a very complex relationship: at low intensities a slight negative slope is evident; at higher intensities the result is non-monotonic in behaviour.
High refining intensity treatments in Figure 10 show no development in the tensile index and significant loss in the tear strength, as the high intensity results in deleterious fibre cutting. When moving to lower intensities fibre cutting reduces, and fibre fibrillation becomes dominant; here seen as increased tensile index and lesser tear loss.

To help simplify this complex relationship, our two stage methodology is outlined below.

5.2.1 Stage 1 – Relationships between operational conditions and fibre properties

Stage 1 will proceed in two steps; first step to study the power and gap relationship, and second step to relate change in freeness to refiner operating conditions.

The number of variables in the LC refining process elevates the importance of proper scaling between different size refiners. To reduce the number of independent refining variables, and to seek proper scaling amongst different size LC refiners, the dimensional analysis technique is used.

Each physical refining parameter is a combination of the dimensions of mass, length, and time. In dimensional analysis one variable is selected to act as one of these dimensional scales. The remaining refining variables are then nondimensionalized with a combination of the selected dimensional scales. This produces a number of nondimensional groups which are well suited for statistical model creation intended for this study.

In this work we considered the net power, $P_{\text{net}}$, to be a function of pulp density $\rho$ (approximated as water for low consistencies of 4%), refiner diameter $D$, rotational speed $\omega$, plate gap $G$, mass flow rate $\dot{m}$, plate design $BEL$, and fibre length $FL$:

$$P_{\text{net}} = f(\rho, D, \omega, G, \dot{m}, BEL, FL)$$  \hspace{1cm} \text{Eq.(8)}
To scale this relationship, we select $\rho$, $\omega$, and $D$ as the dimensional scales:

$$\frac{P_{\text{net}}}{\rho \omega^3 D^5} = f \left( \frac{D}{G}, \frac{m}{\rho \omega D^3}, \frac{BEL}{D}, \frac{FL}{D} \right)$$  \hspace{1cm} \text{Eq.}(9)$$

The outcome of this methodology is a number of derived dimensionless groups that have been used by other researchers. For example the net power number, $\frac{P_{\text{net}}}{\rho \omega^3 D^5}$ was first introduced by Herbert and Marsh [36]. The Power Number scaling is also associated with mixer calculations, where required mixer powers are calculated according the equation above to provide proper mixing results. In a similar manner results shown by Mohlin indicate a linear relationship between refiner motor power and the inverse of gap size [44], here nondimensionalized with diameter, $\frac{D}{G}$.

The results will be presented in terms of this nondimensional framework. We first present the results from the pilot trials, and then move onto the findings from the industrial refiners. To begin, the pilot trial data is shown in Figure 11, as the net power number is plotted as a function of the dimensionless gap. It must be stated that the refiner diameter is constant for this data set. In addition, we present a limited data set representing cases where only virgin fibre was passed through the refiner. We do so to eliminate any effects of changes in the properties of the incoming feedstock.
The Net Power Number is shown to be somewhat linearly related to the inverse of the dimensionless gap for the range of rotational speeds, powers, flow rates, and feed pulps tested at pilot scale. The linear relationship between power and inverted gap agrees with the findings of Mohlin [44]; Leider and Nissan used the inverse of gap to “compute the energy dissipation due to the presence of a shear field” [49].

Next the effect of refiner diameter is studied. Refiner diameter is an important variable, as various different size LC refiners can be found in the industry, and literature shows limited research for scaling between refiner sizes. We have an elevated interest in diameter as it is selected as our dimensionless length scale.
Figure 12 Correlation between net power number and dimensionless gap for both pilot and mill trials

Figure 12 shows the collected mill data in addition with pilot data, now for the complete pilot data set with subsequent refining passes. Compared to the first pass pilot data in Figure 11, the mill data also shows approximate linear trends, however with different slopes.

The pilot trial data for subsequent refining passes shows increased deviation from the linear trend in Figure 11 for trials • and ▲, where gap size decreases to maintain constant motor power required by the pilot trial protocol. As these two trials have a high refining intensity, the decrease in gap size is hypothesized as a result of increased fibre cutting. For the pilot trial protocol used, discharge pulp becomes feed for the subsequent refining pass; increased cutting decreases feed pulp fibre length for the following pass. We cannot see this phenomenon with the mill trial because of the different trial protocol, where mill refiners maintain similar feed pulp properties through the trials.
We study the relationship between fibre cutting and gap size in Figure 13, reporting only the mass fraction of the suspension representing the long fibres, i.e. the accumulated mass of the R14, R28, and R48 Bauer-McNett fractions; referred to as the Long Fibre Fraction (LFF). The sum of the selected Bauer-McNett Fractions is used as an approximation of fibre length; correlation between fibre length and the LFF can be seen in Appendix 1.

Figure 13 shows a critical gap size at approximately 0.3mm below which fibre length diminishes dramatically. As hypothesized, trials • and ▲ which deviate from the linear trend in Figure 12 correspond to the greatest decrease in fibre length. This gives indication for the importance of fibre length in the correlation between power and gap. It should be stated that the critical gap size of 0.3mm in Figure 13 is by no means universal, and should therefore be experimentally determined for each
refiner and feed pulp separately; though a similar critical gap size for increased fibre cutting has been shown by Mohlin [50] for a 0.61m (24") double disc laboratory refiner. Both Mohlin and Lundin [51] find that the critical gap changes with feed pulp properties and consistency.

For the pilot refiner tested we propose the following relationship for changes in fibre length:

\[ G \geq G_{\text{crit}}, \quad LFF_{out} = 0.98 \cdot LFF_{in} \]

\[ G < G_{\text{crit}}, \quad LFF_{out} = \left( h \cdot \ln \left( \frac{G}{G_{\text{crit}}} \right) + 0.98 \right) LFF_{in} \]

Eq.(10)

For gap sizes above critical (for the pilot refiner data \( G_{\text{crit}} = 0.3 \)), the constant presented in Equation 10 is an average for the \( LFF_{out}/LFF_{in} \) data in Figure 13. For gap sizes bellow critical fibre length decreases rapidly; coefficient \( b \) is proposed as a function of refiner operating variables (for the pilot refiner data \( h = 0.14 \)). The refiner data collected does not show general correlations for neither \( G_{\text{crit}} \) or \( b \).

The pulp mass flow rate is the last nondimensional group studied, and shows poor correlation with the net power number in Figure 14. This is an expected result, as LC refiner power and flow rate should be decoupled. Because of this poor correlation, the dimensionless mass flow rate is not included in the following statistical study between power and gap.
Before moving on to create the statistical model between the dimensionless groups, it should be mentioned that refiner plate design is included in the model as literature indicated that fibres are transported to the gap by the leading edge of the rotor bar [52].

From the observed relationships between our dimensionless groups in Equation 9, correlation is sought for an exponential multiple regression form. A total of 112 data points are used for a least square fit to solve for the regression coefficients, and the following values are obtained, see Appendix 3. for statistical analysis:

\[
\frac{P_{net}}{\rho \omega^3 D^5} = 0.03 \cdot \left(\frac{D}{G}\right)^{0.8} \cdot \left(\frac{F_{lin}}{D}\right)^{1.3} \cdot \left(\frac{BEL}{D}\right)^{0.5}
\]

Eq.(11)
To determine the quality of the proposed correlation between the nondimensional groups, measured net power number values are plotted with values from the proposed model, Figure 15.

A fit following the diagonal line in Figure 15 indicates a good correlation between the predicted and measured net power number values, $R^2 \approx 0.84$, and the remaining variation can be seen as linear trends with deviating slopes from the diagonal line. Regardless of the variation, the three dimensionless parameters of gap size, fibre length, and plate design seem sufficient to predict refiner net motor load for the range of conditions tested.

*Figure 15 Correlation between the predicted and measured net power number from Equation 11*
To study the linear relationship between the inverse of gap and refiner power seen in data from Mohlin [44], we roundup the other regression coefficients to the closest approximate values and solve for a new constant; obtaining the following:

\[
\frac{P_{\text{net}}}{\rho \omega^3 D^2} = 0.008 \cdot \left(\frac{D}{G}\right)^1 \cdot \left(\frac{FL}{D}\right)^2 \cdot \left(\frac{BEL}{D}\right)^{\frac{1}{2}}
\]

Eq.(12)

Similarly to the previous model proposed, the quality is estimated by plotting measured net power number values with predicted values from the proposed model, Figure 16.

Figure 16 Correlation between the predicted and measured Power Number for approximated coefficients from Equation 12
For the approximated regression coefficients a similar correlation is seen between the predicted and measured net power number, adjusted $R^2 \approx 0.70$, and Equation 12 can be simplified to the form of:

$$\frac{P_{net}}{\rho \omega^3 D^5} = 0.008 \cdot \left( \frac{FL^2}{G \cdot D} \right) \cdot \left( \frac{BEL}{FL} \right)^{\frac{1}{2}}$$  \hspace{1cm} \text{Eq.(13)}$$

As the second fibre property, we now create a statistical model to predict freeness changes from LC refiner operating conditions. We begin by creating a plot for freeness and dimensionless Net Specific Energy (NSE), Figure 17. The Net Specific Energy is nondimensionalized with both rotational speed and diameter squared.

The freeness development in Figure 17 shows greater freeness drop for higher freeness feed pulps with a given energy. The range of applied dimensionless NSE is notably greater for the pilot data, as pilot and mill refiners are tested according to different protocols. For the pilot refiner the NSE is increased without a physical limit by running multiple passes through the refiner, whereas at the mill refiner energy is increased by increasing motor load, respectively decreasing gap, for a given flow rate. Mill refiners are therefore limited for the maximum available NSE by both refiner motor size and a minimum flow rate requirement.

Both pilot and mill data show similar trends in Figure 17, and a general exponential form is proposed:

$$CSF_{out} = CSF_{in} \cdot e^{-k \cdot \frac{NSE}{\omega^3 D^5}}$$  \hspace{1cm} \text{Eq.(14)}$$

Here $CSF_{out}$ and $CSF_{in}$ represent discharge and feed freeness' respectively, and $k$ is considered as the freeness drop coefficient for LC refining of mechanical pulp.
Because of the different protocol between pilot and mill refiners, the pilot data will be considered as single passes through the refiner. Now values for the freeness drop coefficient $k$ can be calculated by rearranging Equation 14:

$$-k = \ln \left( \frac{CSF_{\text{out}}}{CSF_{\text{in}}} \right) \frac{NSE}{\omega^2D^2} \quad \text{Eq.(15)}$$

Since the Net Specific Energy in Equation 14 represents the amount of energy applied, we will create a model for the freeness drop coefficient $k$ to describe the mode in which the energy is applied, i.e. intensity. Instead of using the popular $SEL$ theory to estimate refining intensity, we propose to use gap size. This approach is taken from Mohlin who stated that [44]: “Plate gap and the power input have a
large effect on the refining result and that they should be looked at as the primary variables in refining instead of measures of refining intensity”.

Based on the trends in Figure 17 and suggestions of Mohlin, we propose the freeness drop coefficient $k$ to be a function of dimensionless feed freeness, nondimensionalized by diameter cubed, and dimensionless gap. A total of 168 data points are used for the least square fit to solve for the regression coefficients which gives the following, see Appendix 3:

$$k = \left(\frac{CSF_{in}}{D^3}\right)^{-0.82} \cdot \left(\frac{D}{G}\right)^{-1.41} \tag{Eq.(16)}$$

This can then be substituted back into Equation 14 to yield to final predictive model for discharge freeness:

$$CSF_{out} = CSF_{in} \cdot e^{-\left(\frac{CSF_{in}}{D^3}\right)^{-0.8} \cdot \left(\frac{D}{G}\right)^{-1.4} \cdot \frac{NSE}{\omega^2 D^2}} \tag{Eq.(17)}$$

To determine the quality of the proposed model, measured values are plotted with the values from the predictive model in Figure 18. A great fit around the diagonal line is seen, $R^2 \approx 0.98$, as proof that discharge freeness can be predicted from the dimensionless groups for feed freeness, gap and Net Specific Energy.
5.2.2 Stage 2 – Relationships between fibre and pulp properties

In the previous section we presented predictive models between LC refiner operating conditions and two key fibre properties of length and freeness. In the second stage of our proposed methodology we build on the work of Forgacs [1] and his hypothesis that: “the structural composition of mechanical pulps is defined in terms of two factors, namely distribution by weight of fibre length, and a characteristic particle shape parameter, which was related to the bonding potential of the particles in mechanical pulps”.

Figure 19 a), b), and c), show figures which correlate the most common paper properties of tear index, bulk and tensile index to the key fibre properties of Long Fibre Fraction (LFF), i.e. the accumulated mass of the R14, R28, and R48 Bauer-McNett fractions and freeness.
Figure 19a indicates one general exponential trend between the tear index and the Long Fibre Fraction for all different pulps, refiner diameters, and operating conditions tested. In a similar manner, bulk scales nicely with freeness in Figure 19b. The tensile index shows correlation with the LFF squared over freeness in Figure 19c. This relationship was acquired from a least square fit to the pulp property data from the pilot trials, where the estimated coefficients for the LFF and freeness were approximately 2 and -1.

These results further validate the hypothesis of Forgacs, where mechanical pulp properties can be predicted from key fibre properties of length and freeness; he reports $R^2$ values of 0.86 and 0.90 for tear and tensile for the 36 miniature grinder pulp samples. For the 155 samples from 8 different refiners we indicate $R^2$ values of 0.90 and 0.78 respectively; $R^2$ values increase to 0.94 and 0.90 when limited to the pilot refiner samples.
Figure 19  

a) Correlation between tear index and the long fibre fraction  
b) Correlation between bulk and freeness  
c) Correlation between tensile index and long fibre fraction squared over freeness
5.2.3 Discussion of proposed framework

In the previous two stages we have introduced our methodology to relate refiner operating conditions to resulting pulp properties via two key fibre properties of length and freeness. In this discussion our purpose is to provide the reader with some “rules of thumb” as an example of the framework.

We start with the Specific Edge Load theory, as it is the most commonly used characterization of refining intensity in the industry. The SEL is considered as a machine intensity, and does not provide accurate prediction of the resulting refining action. This is seen in Figure 20, where SEL values are plotted with the interpolated tensile index increase at 200 kWh/ton (only pilot data is shown to remove the effect of wood species and refiner diameter).

Significant scatter is seen in Figure 20, but a linear trend can be approximated for greater tensile index increase with decreasing specific edge load intensity. However, there is clear indication that SEL does not fully characterize the refining action; especially the fully effect of changing rotational speed is not captured seen as greater deviation in the 120ml feed freeness trials (blue symbols). Similar lack of correlation between tensile strength and SEL was shown by Croney et al.[53] studying LC refining of both soft- and hardwood pulps.

If the SEL intensity is replaced by the gap size, a measurable refining variable, better parabolic trends can be seen in Figure 21a; blue trend line presents 120ml, green 350ml, and red 500ml feed freeness pulp. An optimum gap size for maximum tensile development is identified which increases with increasing feed pulp freeness. Here, fibre length increases with increasing feed freeness which is hypothesized to correlate with the increasing gap size.
Figure 20 Interpolated tensile index increase @ 200 kWh/ton for different intensities calculated by the Specific Edge Load theory

Figure 21b illustrates three gap ranges using the 120 ml feed freeness pilot trials as an example. Maximum tensile increase occurs at the optimum gap sizes between 0.35-0.7mm, where proper refining intensity is achieved for optimum fibre fibrillation. To the left of the optimum, gap sizes smaller than 0.35mm, intensity increases and deleterious fibre cutting occurs; previously shown in Figure 13. To the right of the optimum, gap sizes greater than 0.7mm, the refining intensity is insufficient to create permanent deformations in the fibre cell wall, and energy is consumed by the elastic deformations instead.

Although the physical mechanism for fibre development in LC refining still remains unknown, we have been able to identify an optimum gap size, a physical refining variable, as a better estimator of refining intensity compared to the commonly used Specific Edge Load intensity.
Figure 21  

a) Interpolated tensile index increase @ 200 kWh/t with corresponding plate gap  
b) Three different gap ranges for tensile index increase @ 200 kWh/ton  

Color of the trend line present pulp feed freeness: blue 120ml, green 350ml, and red 550ml.
The relationship between tensile development and gap size is a result of the forces acting on the fibre flocs captured in the gap by the leading edges of the refiner plate bars. Both shear and normal forces are imposed on the flocs in a cyclic manner to create new fibre surfaces by external fibrillation and fines generation, as well as increasing fibre flexibility by compressions the lumen. The forces are imposed by the complex interactions of the refiner operating conditions and the properties of the pulp suspension refined. The cause-and-effect of forces changing fibre morphology are difficult to decouple as after each cyclical loading the floc fibre matrix is redistributed by the turbulent flow in the grooves before being captured by the following bar leading edge. For the following loading cycle the rearranged fibres are now refiner at different locations and in different directions.

As a generalization, the cause-and-effect for both internal and external fibrillation can be separated, but not limited to, by the different forces imposed on the floc fibre matrix. Internal fibrillation is increased with the normal forces by first compressing the floc to a fibre-fibre contact, followed by the compression of the fibre lumens. The cyclic compressions of the fibre lumen increase fibre swelling as well as the fibre collapsibility; an important property effecting resulting paper smoothness. The pulp compressibility varies with wood species type as well as the degree of existing fibre flexibility; at similar energies Figure 21b shows an increasing gap size for higher freeness pulps made of similar species. External fibrillation and fines creation are increased by the abrasive “brushing” of the flocs over the bar width; this can be considered as the primary mode of fibre cutting assuming a tensile type failure, however cutting may result from extensive compression of the fibre wall as well.

As a general observation of the relationships between fibre development and refiner operating conditions, it is concluded that the effect of both the type of wood species and the forces on fibres are to be better understood for a complete picture of the LC refining action; see Recommendation.
5.2.4 **Error analysis**

The source of error for the statistical models proposed originates from the various methods used to measure both refiner operational variables and pulp quality.

For both pilot and mill trials the primary refining variables of refiner motor power and pulp flow rate were recorded by the refiner control system, which neither recorded nor monitored the variation of these variables. Refiner motor power is controlled by altering the total gap between the two stators; when motor power falls below the control system set point, the stepper motor and screw combination (see Figure 2) decreases the gap and motor power varies until the floating rotor reaches a steady state. The sensors monitoring both motor power and pulp flow rate were assumed to be calibrated and functioning properly.

The pulp properties were measured in three different laboratories by three different technicians using three different sets of equipment. The possibility for human error is acknowledged, however it cannot be corrected for; the standard methods used for the pulp quality measurements are well established, and a 5% method error is reported.

The estimates of plate gap size were measured with the external LVDT using a high sampling frequency to capture both variation and vibrations in the system. This method measures the relative distance between the two stators, and is divided by two to estimate the gap size in either refining zone. The hypothesis for an equal gap size in both refining zones is incorrect, but the use of an external sensor does provide a fast and affordable method to estimate changes in the gap size without physically altering the construction of the refiner. The measured standard deviation for the relative movement of the far-side refiner housing during steady state operations is on average approximately $3.5 \times 10^{-3}$ mm; 95% of the measured values are within $\pm 0.008$ mm of the mean estimated gap size.
The previously created statistical models are affected by the errors stated above, and the significance levels of the regression coefficient can be estimated from the standard error value presented in Appendix 3. Upper and lower confidence limits can be calculated by multiplying the standard error with the desired value of normal distribution; for a 95% confidence level this is approximately 1.96. The confidence limits of the regression coefficients for the dimensionless groups are shown in TABLE 3:

**TABLE 3 Upper and lower 95% confidence limits for the statistical regression coefficients**

<table>
<thead>
<tr>
<th>Dimensionless group</th>
<th>Power Number</th>
<th>Freeness Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D \over G$</td>
<td>$F_{\text{lin}} \over D$</td>
</tr>
<tr>
<td>Regression Coefficient</td>
<td>0.751</td>
<td>1.306</td>
</tr>
<tr>
<td>Upper &amp; lower 95% confidence limit</td>
<td>±0.078</td>
<td>±0.233</td>
</tr>
</tbody>
</table>
5.3 Conclusion

Our new two-stage methodology is presented to provide correlations between LC refiner operating conditions and resulting changes in mechanical pulp quality. In the first stage we advance a critical gap size for fibre cutting and two statistical models to correlate refiner operating conditions to key pulp properties of length and freeness:

\[ G \geq G_{\text{crit}}, \quad LFF_{\text{out}} = 0.98 \cdot LFF_{\text{in}} \]

\[ G < G_{\text{crit}}, \quad LFF_{\text{out}} = \left( h \cdot \ln \left( \frac{G}{G_{\text{crit}}} \right) + 0.98 \right) LFF_{\text{in}} \]

\[ \frac{P_{\text{net}}}{\rho \omega^3 D^5} = 0.03 \cdot \left( \frac{D}{G} \right)^{0.8} \cdot \left( \frac{FL_{\text{in}}}{D} \right)^{1.3} \cdot \left( \frac{BEL}{D} \right)^{0.5} \]

\[ CSF_{\text{out}} = CSF_{\text{in}} \cdot e^{-\left( \frac{CSF_{\text{in}}}{D^2} \right)^{-0.8} \cdot \left( \frac{D}{\tau} \right)^{-1.4} \cdot \frac{NSE}{\omega^2 p^2}} \]

The second stage of the methodology builds on the work of Forgacs, and we show that mechanical pulp properties are correlated to our key fibre properties. With this two-stage correlation methodology, we develop ``rules of thumb'' to relate operating variables directly to final paper properties, and demonstrate how gap is a better indicator of refining intensity than the calculated intensity of the Specific Edge Load theory. Maximum tensile development is shown for an optimal gap, which is found to increase with increasing feed freeness.
6. DEMONSTRATION OF POTENTIAL TMP ENERGY SAVINGS PROVIDED BY MULTI-STAGE LC REFINING

An improved TMP process is presented, where potential energy savings are studied by replacing the secondary stage HC refiner by multiple stages of LC refining, Figure 22. The single stage of HC refining and multi-stage LC refining is expected to produce similar final pulp properties compared to a conventional 2 stage HC refining TMP process when LC refining energy is applied without significant fibre cutting.

6.1 Experimental

The improved TMP process with a single HC refining stage and multi-stage LC refining is studied at pilot scale. Pilot trials are conducted at the same Andritz R&D facility in Springfield, Ohio, as previous pilot trials. Whole log hemlock wood chips were shipped from coastal British Columbia to the pilot plant to assure similar fibre supply to the local pulp mills.
Chip refining at the primary HC stage is done with a 0.91m (36”) HC refiner, Andritz model 36-1CP™, after which the high freeness pulp is chelated, dewatered in a twin wire press, and stored in 200 liter barrels at the consistency of 35%. LC refining is conducted with the same protocol and refiner (0.56m (22”) Andritz TwinFlo™) as presented in the previous Chapter. Three different motor loads are selected, and remaining refining variables kept constant: 4% consistency, 4.4 kg/s mass flow rate, 1200 RPM rotational speed, 167 kW no-load, and 14.65 km/rev Bar Edge Length. Operating conditions for trials presented are in TABLE 4.

### TABLE 4 LC refiner operating conditions for trials presented

<table>
<thead>
<tr>
<th>FEED FREENESS</th>
<th>NET MOTOR POWER</th>
<th>GAP RANGE</th>
<th>APPLIED NSE per pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ml]</td>
<td>[kW]</td>
<td>[J/m]</td>
<td>[mm]</td>
</tr>
<tr>
<td>390</td>
<td>56</td>
<td>0.19</td>
<td>0.55-0.70</td>
</tr>
<tr>
<td>390</td>
<td>83</td>
<td>0.28</td>
<td>0.37-0.58</td>
</tr>
<tr>
<td>320</td>
<td>99</td>
<td>0.34</td>
<td>0.18-0.35</td>
</tr>
</tbody>
</table>

### 6.2 Results

Our objective in this chapter is to demonstrate potential energy savings for the improved TMP process by creating equal quality mechanical pulp compared to a conventional two-stage HC process. Baseline data for the conventional process is collected from a British Columbia pulp mill running a similar species mix. This mill reaches its pulp quality targets of approximately 120ml freeness with a tensile index of 38 Nm/g with an average of 3100 kWh/ton, TABLE 5. Here we concentrate on these two quality parameters, and development of the remaining quality variables can be found in Appendix 2.
Next a similar freeness value is interpolated from the multi-stage LC refining curves in Figure 23a for the cumulative Net Specific Energy of the HC and LC refining stages, approximately 1210 kWh/ton. Similarly in Figure 23b we interpolate a value for the tensile index at the freeness of 120ml to be approximately 38 Nm/g. This validates our hypothesis of creating equal quality mechanical pulp by replacing the second stage HC refiner with multi-stage LC refining, for example 2 stage of 150 kWh/ton per stage (solid orange squares in Figure 23).

The energy consumption data of the conventional TMP baseline process is broken down according to process stages in TABLE 5. To estimate potential energy savings, the last two stages of Reject Refining and Miscellaneous are kept constant for the improved TMP process, as the effect of increased LC refining on these stages remains unknown.

**TABLE 5 Net specific energy break down between the conventional and proposed TMP process**

<table>
<thead>
<tr>
<th>All values in [kWh/ton]</th>
<th>Primary HCR</th>
<th>Secondary HCR</th>
<th>Tertiary LCR</th>
<th>Reject Refiner</th>
<th>Misc.</th>
<th>Total</th>
<th>Estimated Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional TMP</strong></td>
<td>900</td>
<td>900</td>
<td>100</td>
<td>600</td>
<td>600</td>
<td>3100</td>
<td>-</td>
</tr>
<tr>
<td><strong>Improved TMP</strong></td>
<td>910</td>
<td>-</td>
<td>2 x 150</td>
<td>600</td>
<td>600</td>
<td>2410</td>
<td>690</td>
</tr>
</tbody>
</table>

Estimated energy saving for the improved TMP process with a single HC refining stage followed by two stages of LC refining at 150 kWh/ton is approximately 700 kWh/ton, or over 20%, compared to the conventional TMP process with two HC refining stages and a single LC refining stage. If we only compare the refiner specific energy in the highlighted box in TABLE 5, the improved TMP process reduces energy consumption over 35%.
Figure 23 a) Interpolated cumulative net specific energy of the HC and LC refining stages to achieve 120ml freeness
b) Interpolated tensile index for the 120ml freeness pulp
6.3 Conclusions

Energy savings are demonstrated in pilot scale for an improved TMP process using a single HC refining stage followed by multi-stage LC refining. In comparison to a conventional TMP process, energy consumption is reduced by approximately 700 kWh/ton, or over 20%, to create mechanical pulp of equal quality. A mill scale application of a similar process has shown 40-50% lower electrical energy consumption compared to conventional HC refining [54].

We conclude that LC refiners are greater in energy efficiency compared to second stage HC refiners for developing mechanical pulp quality after the primary HC refining stage. As the physical reason for the increased efficiency remains unknown, we hypothesize it as a result of the greater uniformity in refining treatment.

In this chapter we can also study the effect of different net specific energy per LC refining pass (90, 125, and 150 kWh/ton), and find that each trial follows the same freeness drop curve. Fibre cutting does increase with increasing net specific energy per pass, seen in Appendix 2, but gap size never falls below the critical value of 0.3mm within our range of interest.
7. SUMMARY OF CONTRIBUTIONS

In this dissertation we present a new two-stage methodology to correlate LC refiner operating conditions to mechanical pulp quality. A wide range of refiner sizes and operating conditions were tested to allow us study the scaling between different refiners.

In the first stage of the methodology we advance a critical gap size and two statistical models based on dimensional analysis to correlate refiner operating variables with the key fibre properties of length and freeness:

\[ G \geq G_{\text{crit}}, \quad LFF_{\text{out}} = 0.98 \cdot LFF_{\text{in}} \]
\[ G < G_{\text{crit}}, \quad LFF_{\text{out}} = \left( h \cdot \ln \left( \frac{G}{G_{\text{crit}}} \right) + 0.98 \right) LFF_{\text{in}} \]

\[ \frac{P_{\text{net}}}{\rho \omega^4 D^5} = 0.03 \cdot \left( \frac{D}{G} \right)^{0.8} \cdot \left( \frac{F L_{\text{in}}}{D} \right)^{1.3} \cdot \left( \frac{BEL}{D} \right)^{0.5} \]

\[ CSF_{\text{out}} = CSF_{\text{in}} \cdot e^{-\left( \frac{CSF_{\text{in}}}{D^3} \right)^{-0.8} \cdot \left( \frac{D}{G} \right)^{-1.4} \cdot \frac{NSE}{\omega^2 D^2}} \]

The second stage on the methodology is built upon the work of Forgacs [1], and his hypothesis that: “the structural composition of mechanical pulps is defined in terms of two factors, namely distribution by weight of fibre length, and a characteristic particle shape parameter, which was related to the bonding potential of the particles in mechanical pulps”. In the second stage of our methodology we approximate these two factors with key fibre properties of length and freeness, and confirm earlier findings of Forgacs [1] for correlations with mechanical pulp properties of tear index, bulk, and tensile index.
We then provide the reader with some “rules of thumb” to optimize mechanical pulp quality development in LC refining, in this case how to maximize tensile strength. First we demonstrate that gap size is a better estimator of refining intensity than the commonly used specific edge load intensity. The increase in tensile index is shown to correlate with gap size, and an optimum gap is identified where the refining intensity is sufficient to create optimum fibre fibrillation. Gap sizes smaller than the optimum increase refining intensity and result as increased fibre cutting. Similarly greater gap sizes cannot provide a refining intensity great enough to create permanent changes in fibre morphology and energy is lost in elastic deformations. Both optimum gap size and maximum tensile increase are shown to increase with feed pulp freeness.

Finally we demonstrate energy savings for an improved TMP process with a single HC refining stage to comminate wood chips to individual fibre followed by multi-stage LC refining. Compared to a conventional TMP process with two HC refining stages and a single stage of LC refining, the improved TMP process demonstrates energy reduction in pilot scale by approximately 700 kWh/ton, or over 20% to create mechanical pulp of equal quality.

This dissertation shows the greater energy efficiency of LC refiners to develop mechanical pulp quality compared to second stage HC refiners. To fully capitalize on the increased efficiency of LC refiners, they are to be correctly controlled. Optimum mechanical pulp quality development takes place at a specific combination of operating conditions, which can be estimated by the models created from our new two-stage methodology.
8. RECOMMENDATIONS

Latest research in low consistency refining focuses on the forces acting on the fibres [43], and these forces can be hypothesized as a function of the refiner operational variables and the pulp suspension properties. In the mechanical pulping process the pulp suspension properties fluctuate continuously and the time required to adequately characterize the key suspension properties is time-consuming, therefore unsuitable as a control variable for the low consistency refiner. With better understanding of the correlations between the forces on fibres, refiner operational variables, and resulting pulp quality changes, a new low consistency refiner control logic can be developed. The logic should measure forces, and control them by altering plate gap; in an industrial refiner most of the other operational variables are kept constant. Both forces and gap size can be measured at high frequencies and rapidly controlled to provide a constant force on the fibres.

Another important variable affecting pulp quality development in LC refining is the refiner plate geometry. Current refiner plates are characterized according to the BEL-theory (Eq. 1); a limited method as similar BEL values can be calculated for different combinations of bar and groove widths. A better refiner plate geometry characterization is required to correlate effects of the different plate design variables to pulp quality development by means of the forces on fibres.

The final recommendation is for a new definition of LC refiner no-load; currently no standard exists for the measurement of no-load power. The no-load power has a significant effect characterizing the refining action as it is deducted from the total motor power to give the net power used to alter fibre morphology. Rather than measuring the power to rotate the refiner with the plates fully backed open, a methodology is required to estimate the power used by the refiner for purposes other than changes in fibre morphology.
REFERENCES


APPENDICES

Appendix 1. Long fibre fraction versus fibre length

Regardless of the scatter in Figure 24, fibre length is seen to correlate with the measured Long Fibre Fraction, data shown for both pilot and mill trials.

Figure 24 Correlation between Bauer-McNett fractions R14+R28+R48, Long Fibre Fraction (LFF) and measured fibre length.
Appendix 2. Improved TMP processes pulp quality development

In this appendix we show pulp quality development for the improved TMP process compared with development the market TMP pulp from previous tests. Direct comparison of the data is impossible because of the different wood species: market TMP is a mix of spruce, pine, and fir, whereas the improved TMP is made of hemlock. Also we have no information for the cumulative HC refining energy for the market TMP pulps, and therefore pulp quality development is compared with pulp freeness.

For the market TMP data we select trials with the same refiner plate design, and rotational speed as used with the improved TMP process. Difference in operating conditions is in the flow rate and feed freeness detailed in TABLE 6.

| TABLE 6 Operating conditions for market and enhanced TMP LC refining trials |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| FEED FREENESS   | PULP FLOWRATE   | NET MOTOR POWER | NO-LOAD MOTOR POWER | GAP RANGE | APPLIED NSE per pass |
| [ml]            | [kg/s]          | [1/s]           | [kW]              | [kW] | [J/m] | [mm] | [kWh/ODMT] |
| 120             | 6.7             | 20.00           | 59                | 167 | 0.20 | 0.72-0.78 | 60 |
| 350             | 6.7             | 20.00           | 58                | 167 | 0.20 | 0.69-0.73 | 59 |
| 550             | 6.7             | 20.00           | 57                | 167 | 0.19 | 0.72-0.83 | 60 |
| 390             | 4.4             | 20.00           | 56                | 167 | 0.19 | 0.55-0.70 | 90 |
| 390             | 4.4             | 20.00           | 83                | 167 | 0.28 | 0.37-0.58 | 127 |
| 320             | 4.4             | 20.00           | 99                | 167 | 0.34 | 0.18-0.35 | 153 |
First we will study key fibre properties of length and freeness. The improved TMP refining trials show a greater decrease in freeness, especially when compared with green symbols for the market TMP trials with a similar feed freeness of approximately 350ml, Figure 25a. We consider this as a result of the different wood species used. Similar decrease the ratio long fibre fraction (LFF) in and is seen in Figure 25b when the gap size falls below the critical value of 0.4mm; increase in the critical gap size is hypothesized as change in wood species and the prior refining stages. Here greater motor power requires a smaller gap, and results in increased fibre cutting for higher net specific energy per pass.

Similarly to the freeness drop, tensile index increases independently from the net specific energy per pass in Figure 26a. The tensile index increase for the improved TMP process shows a similar slope compared to market TMP trials, however the initial tensile index is approx. 10 units lower than the market TMP at similar freeness (green squares). A somewhat similar conclusion can be given for the bulk-freeness graphs in Figure 26b, with the exception that the improved TMP process shows a higher bulk at a given freeness. This is also proposed as a result of the different wood species used.

As the remaining common mechanical pulp property, we now examine the tear index. The tear-tensile relationship in Figure 27a shows lower tear values for the improved TMP process at a given tensile index compared to the market TMP trials, a result of the different wood species. For the increasing net specific energy per pass a greater decrease in tear is seen, however the tear decrease does not become dominant until tensile index' over 40 Nm/g.

Figure 27b shows the relationship between tear index and long fibre fraction (LFF), and we see one uniform trend for the range of operating conditions tested.
Figure 25 a) Freeness drop with increasing net specific energy for both improved and market TMP
b) Ratio of long fibre fraction (LFF) before and after refining plotted for matching gap
Figure 26 a) Tensile index and freeness relationship for both enhanced and market TMP trials
b) Bulk and freeness relationship for both enhanced and market TMP trials
Figure 27 a) Tear-tensile relationship for both enhanced and market TMP trials
b) Relationship between tear index and long fibre fraction (LFF)
Appendix 3. Statistical model analysis

**Power Number**

**Call:** lm(formula = log(ndPnet[1:y]) ~ log(ndGAP[1:y]) + log(ndLWAFL[1:y]) + log(ndBEL[1:y]))

Residuals:

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<th>Min</th>
<th>1Q</th>
<th>Median</th>
<th>3Q</th>
<th>Max</th>
</tr>
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**Coefficients:**

|                | Estimate | Std. Error | t value | Pr(>|t|) |
|----------------|----------|------------|---------|----------|
| (Intercept)    | -3.50611 | 0.27918    | -12.56  | <2e-16 *** |
| log(ndGAP[1:y]) | 0.75120  | 0.03998    | 18.79   | <2e-16 *** |
| log(ndLWAFL[1:y]) | 1.30582  | 0.11860    | 11.01   | <2e-16 *** |
| log(ndBEL[1:y]) | 0.46093  | 0.04532    | 10.17   | <2e-16 *** |

---

Signif. codes:  0 ‘****’ 0.001 ‘***’ 0.01 ‘**’ 0.05 ‘*’ 0.1 ‘ ’ 1

Residual standard error: 0.2447 on 108 degrees of freedom

Multiple R-squared: 0.8435, Adjusted R-squared: 0.8391

F-statistic: 194 on 3 and 108 DF, p-value: < 2.2e-16
Freeness drop coefficient “k”

Call: lm(formula = log(kexp[1:x]) ~ log(ndCSFin[1:x]) + log(ndGAP[1:x]) - 1)

Residuals:

<table>
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<tr>
<th></th>
<th>Min</th>
<th>1Q</th>
<th>Median</th>
<th>3Q</th>
<th>Max</th>
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</thead>
<tbody>
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</table>

Coefficients:

|                      | Estimate | Std. Error | t value | Pr(>|t|) |
|----------------------|----------|------------|---------|----------|
| log(ndCSFin[1:x])    | -0.8151  | 0.05924    | -13.76  | <2e-16 ***|
| log(ndGAP[1:x])      | -1.4089  | 0.01452    | -97.04  | <2e-16 ***|

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Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.09 on 166 degrees of freedom

(14 observations deleted due to missingness)

Multiple R-squared: 0.9876,   Adjusted R-squared: 0.9875

F-statistic: 6624 on 2 and 166 DF,  p-value: < 2.2e-16