Process intensification in mechanical pulping

Reduced process complexity and improved energy efficiency

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Cover picture: Spruce fibre from an RGP68DD refiner. Dinesh Fernando, SLU, Uppsala, Sweden.

"Life is not as serious as the mind makes it out to be. "

Eckhart Tolle

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Abstract

This work shows that, for newsprint quality grades, the production processes for mechanical pulp can be simplified, and the specific electrical energy demand can be reduced with around 600 kWh/ton (30%). The purpose of the work is to demonstrate how the production cost for mechanical pulps can be decreased through increased energy efficiency and reduced number of unit operations. The idea was to improve the main line refining conditions so that no additional fibre development or shive reduction is needed and thereby, the normal screening and rejects treatment system could be omitted.

Mechanical pulp is used to produce a variety of products, where the two largest categories are printing papers and paperboard for packaging. The pulp is mainly produced by the breakdown of wood chips between rotating metal discs in machines called refiners with the product and process generally referred to as thermomechanical pulp(ing) (TMP). The refiner process requires high specific electrical energy to separate and develop the fibres to a pulp intended for the production of printing papers. Today, many processes need over 2000 kWh/ton of refining energy plus 200-300 kWh/ton of auxiliary energy (to drive pumps, agitators, screw conveyors, screens, presses, etc.).

During the last two decades of the 20th century, the chemical processing industry underwent a transformation. The process development changed from being unit operation focused to function focused. The result is more compact processes with less equipment, higher yield and lower energy demand. When the development is made in an innovative way with such large effects on process performance, it is referred to as process intensification. My work is inspired by the concepts of process intensification, especially the striving for more compact processes with higher efficiency.

This work is focused on mechanical pulp, intended for the manufacture of printing paper, produced in refiners with Norway spruce (*Picea abies*) as raw material. However, this approach could also be applied to mechanical pulp production in integrated paperboard mills and also using other raw materials *e.g.*, pines or hardwoods. The investigated pulps and processes in this work are mainly intended for uncoated paper grades (newsprint, improved newsprint and book paper) printed by the offset printing process. In all studies, the pulps have been produced with full scale mill equipment and evaluated using laboratory measurements. However, in two studies, the produced pulps were evaluated on paper machines and at printing houses.

A large number of process concepts have been evaluated in which different approaches have been used to reduce the specific energy and, in some cases, improve pulp quality. The approaches include:

1. Impressafiner chip pretreatment
2. Primary high consistency (HC) refiner type (DD, RTS, CD, SD)
3. Addition of low doses of sodium sulphite
4. Increased refining temperature (housing pressure)
5. Refiner segments and centre plate design
6. Increased production rate
7. Low consistency (LC) refining in different process positions and in combination with different HC refiner types

The separate effects of all these techniques have not been evaluated systematically neither have potential synergistic effects of all possible combinations been investigated. Even though a large number of combinations of unit operations have been studied, the emphasis has been on trying to do as much fibre development as possible in a single HC refining stage.

The mill trials with spruce as raw material have shown that a low shive content and appropriate fibre development can be attained in a process without separate treatment of long fibres. High intensity primary stage refining (RTS and DD) was necessary to reach a low shive content at a low specific refining energy (SRE), with DD refiners appearing to be the most suitable for simplified processes. DD and RTS refining produced pulps with fibres exhibiting a higher degree of external fibrillation and share of split fibres than SD refining. DD refining produced fibres with lower cell wall thickness and higher light scattering at given fibre length than RTS refining. The lowest specific refining energy was attained for one of the trials using the process, denoted as S:HT:DD-LC-LC, consisting of DD refining at increased production rate, 18 adt/h, increased housing pressure, 6.6 bar(g), and with 5 kg/adt sodium sulphite added to the chips immediately before the refiner. After DD refining the pulp was refined in two LC refining stages. This process required only 1280 kWh/adt SRE to reach a tensile index of 52 Nm/g (Rapid-Köthen). This is 900 kWh/adt lower than the final pulp for newsprint based on SD HC refining, and over 500 kWh/adt lower than Scandinavian BAT processes (2014). Additionally, the auxiliary energy was around 150 kWh/adt lower for the processes without a conventional rejects treatment system. At 52 Nm/g tensile index, the light scattering coefficient was 2-3 m^2/kg higher, and the length-weighted average fibre length was around 0.1 mm lower for this process than for SD TMP final pulp. The fibre bonding, indicated by density, tensile index and Z-strength of fibre fraction handsheets, was similar or higher for the S:HT:DD-LC-LC process than the reference SD TMP process with a rejects treatment system.

Other interesting process configurations, with somewhat lower efficiencies, included:

1. Impressafiner pretreatment of the chips with sodium sulphite before DD refining, with or without subsequent LC refining. Chip pretreatment with the Impressafiner enabled operating the DD refiner at higher intensity (feeding segments and increased production rate) without significant loss of quality and LC refining enabled increased production rate which increased the overall efficiency.
2. RTS-SD refining with sodium sulphite added before the second stage SD refiner referred to as RTS-S:SD. The pulp from the RTS-S:SD process had similar fibre length as the S:HT:DD-LC-LC process but lower light scattering coefficient.
3. A single-stage DD refiner operating at 15.5 adt/h and 4 bar(g) housing pressure (no sodium sulphite addition), which produced pulp with lower fibre length but higher light scattering coefficient than the S:HT:DD-LC-LC process.

Two simplified processes were evaluated on paper machines and in printing houses. The first, denoted DD-LC-F, involved a combination of DD primary refining followed by LC refining and fractionation (screening). The screen rejects were mixed with the main line DD pulp before the LC refiner. The second process was the CPT:S-DD-LC process (№1 above). Good runnability was attained both on the paper machines and in the offset printing presses and the paper quality was similar to the reference paper.

For printing paper applications, the proportion of fibre development in LC refining should preferably be relatively low, since it was shown that LC refiners have limited capacity to reduce fibre wall thickness and thereby develop light scattering and fibre fraction Z-strength.

Explicit effects on the number of unit operations and production cost have not been evaluated in this work, but clearly both investment and variable costs as well as fixed costs can be reduced with a simplified process.

Sammanfattning

Det här arbetet visar att det är möjligt att kraftigt förenkla tillverkningsprocessen för mekanisk massa och samtidigt minska totala elenergibehovet med omkring 600 kWh/ton (30 %) jämfört med dagens bästa teknik. Syftet med detta arbete är att visa hur produktionskostnaden för mekanisk massa kan sänkas genom ökad energieffektivitet och minskat antal enhetsoperationer. Utgångspunkten var att det borde vara möjligt att förbättra betingelserna vid högkoncentrations(HC)raffinering så att det endast krävs ett HC steg och bara mindre efterföljande fiberutveckling. Därmed kan den specifika elenergin minskas avsevärt och det normala rejektbehandlingssystemet uteslutas.

Mekanisk massa används för att producera en mängd olika produkter, där de två största kategorierna är tryckpapper och kartong för förpackningar. Massan framställs huvudsakligen genom att träflis mals mellan roterande metallskivor i maskiner som kallas raffinörer. Separationen och bearbetningen av fibrerna till en massa avsedd för produktion av tryckpapper kräver mycket elenergi. Idag använder många processer över 2000 kWh/ton elenergi för raffinering plus 200-300 kWh/ton elenergi för att driva övrig utrustning, t.ex. pumpar, omrörare, silar, skruvtransportörer, pressar, mm.

Under slutet av 1900-talet genomgick den kemiska processindustrin en genomgripande omvandling. Processutvecklingen gick från att vara fokuserad på enhetsprocesser till att bli funktionsfokuserad. Resultatet är mer kompakta processer med mindre utrustning, högre utbyte och lägre energibehov. När utvecklingen görs på ett innovativt sätt med stor effekt på processprestanda kallas det processintensifiering. Mitt arbete är inspirerat av metodiken inom processintensifiering, särskilt strävan efter mer kompakta processer med högre effektivitet. Arbetet är inriktat på mekanisk massa avsedd för tillverkning av tryckpapper, som produceras i raffinörer med gran (*Picea abies*) som råvara. Metodiken kan dock med stor sannolikhet tillämpas för produktion av mekanisk massa i integrerade kartongbruk och även för andra råvaror, till exempel tall eller lövträ.

De undersökta massaprocesserna i detta arbete är främst avsedda för obestrukna papperskvaliteter (t.ex. tidningspapper, bokpapper och förbättrat tidningspapper) tryckta i offset. I alla studier har massan producerats med stora raffinörer i pappersbruk och utvärderats med hjälp av laboratoriemätningar. I två studier utvärderades dessutom den producerade massan på pappersmaskin och i tryckeri.

Ett stort antal processkoncept har utvärderats där olika metoder har använts för att minska den specifika energin och förbättra massakvaliteten:

1. Flisförbehandling med Impressafiner
2. Typ av HC primärraffinör (DD, RTS, CD, SD)
3. Tillsats av natriumsulfit
4. Ökad raffineringstemperatur (malhustryck)
5. Raffinörsegmentdesign
6. Ökad produktionstakt
7. Lågkoncentrations(LC)raffinering i olika positioner och tillsammans med olika primärraffinörer.

De separata och eventuellt synergistiska effekterna av dessa tekniker har inte utvärderats systematiskt. Även om ett stort antal konfigurationer har studerats, har fokus legat på att försöka göra så mycket fiberutveckling som möjligt i ett enda HC-raffineringssteg.

Fabriksförsöken har visat att låg spethalt och tillräcklig fiberutveckling kan uppnås i en process utan rejektraffineringssystem. HC-raffinering med hög intensitet (RTS och DD) var nödvändigt för att uppnå en låg spethalt vid låg specifik energi, där DD-raffinörer visade sig vara de mest lämpliga. DD och RTS raffinörerna producerade massa vars fibrer hade högre grad av extern fibrillering och mer sprickor i fiberväggen. DD raffinering resulterade i fibrer med tunnare cellväggar och högre ljusspridning vid viss fiberlängd jämfört med RTS raffinering.

Lägst specifik raffineringsenergi erhölls i ett av försöken med en process bestående av DD raffinering vid hög temperatur och med tillsatts av 5 kg/ton natriumsulfit precis före raffinören. Raffinören kördes med hög produktionstakt (18 adt/h) och högt hustryck (6,6 bar(g)). Därefter LC-raffinerades massan i två steg. Denna process, benämnd S:HT:DD-LC-LC, krävde endast 1280 kWh/adt i specifik raffineringsenergi till dragindex 52 Nm/g (Rapid-Köthen), vilket är 900 kWh/adt lägre än en process med SD-raffinering i två steg samt ett normalt rejektsystem och cirka 500 kWh/adt lägre än de bästa processerna i Skandinavien (2014). Dessutom var behovet av övrig elenergi (pumpar, silar, pressar, mm) cirka 150 kWh/adt lägre för en process utan rejektbearbetningssystem. Vid 52 Nm/g i dragindex var ljusspridningskoefficienten 2-3 m^2/kg högre och längdviktade medelfiberlängden cirka 0.1 mm lägre för den förenklade S:HT:DD-LC-LC processen jämfört med färdigmassa från SD TMP. Massan från den förenklade processen hade bättre eller lika bra fiberbindning, bedömd utifrån densitet, dragindex och Z-styrka på fiberfraktionsark, som en SD TMP process med sileri och rejektbearbetning.

Ytterligare intressanta processer som dock hade något lägre energi-effektivitet var:

1. Flisförbehandling med Impressafiner och natriumsulfit följt av DD raffinering, med eller utan efterföljande LC raffinering. Flisförbehandlingen med Impressafiner möjliggjorde högre raffineringsintensitet (Matande segment och hög produktion) och därmed högre energieffektivitet utan att massakvaliteten blev sämre. LC raffinering i huvudlinjen möjliggjorde ökad produktionstakt vilket sammantaget ökade energieffektiviteten.
2. Tvåstegsraffinering med RTS i första steget och SD raffinering i andra steget där 5 kg/adt natriumsulfit tillsattes till massan före andrasteget. Denna process producerade massa med samma fiberlängd som S:HT:DD-LC-LC processen, men med lägre ljusspridning.
3. DD raffinering utan sulfit, men vid relativt hög produktion, 15.5 adt/h, och vid normalt hustryck, 4 bar. Detta är en mycket enkel process som dock resulterade i en massa med lägre fiberlängd men högre ljusspridning än S:HT:DD-LC-LC processen.

Två förenklade processer utan sileri och rejektbearbetning utvärderades på pappersmaskiner och i tryckeri. Den första bestod av DD raffinering i första steget följt av LC raffinering och silning. Silrejektet blandades med DD massan före LC raffinören. Den andra processen inleddes med flisförbehandling med Impressafiner och natriumsulfit följt av DD raffinering och ett LC raffineringssteg. Massorna från de två förenklade processerna uppvisade bra körbarhet på pappersmaskinerna och i tryckerierna och gav liknande pappers-kvalitet som den normala massan, med undantag av något lägre rivstyrka.

Vid tillverkning av massa för tryckpapper är det fördelaktigt att kombinera LC raffinering med flisraffinering som ger hög ljusspridning, till exempel DD-raffinörer. Dessutom bör andelen av den totala bearbetningen vara relativt låg i LC raffineringen eftersom den har begränsad förmåga att minska fiberväggs-tjockleken och därigenom utveckla ljusspridning och fiberfraktionens bindningsförmåga (mätt som Z-styrka).

Effekten på antal enhetsoperationer och produktionskostnaden har inte utvärderats explicit i detta arbete, men det är uppenbart att både investeringskostnad samt rörlig och fast kostnad kan minskas med en förenklad process.

List of papers

This thesis is mainly based on the following papers, herein referred to by their Roman numerals:

Paper I

Effects of chip pretreatment and feeding segments on specific energy and pulp quality in TMP production

Christer Sandberg, Erik Nelsson, Birgitta Engberg, Jan-Erik Berg and Per Engstrand

Nordic Pulp & Paper Research Journal, 2018, 33(3), 448-459.

Paper II

Low consistency refining of mechanical pulp — system design

Christer Sandberg, Jan-Erik Berg and Per Engstrand

TAPPI Journal, 2017, 16(7), 419-429.

Paper III

Low consistency refining combined with screen fractionation: reduction of mechanical pulping process complexity

Christer Sandberg, Jan-Erik Berg and Per Engstrand

BioResources, 2019, 14(1):882-894.

Paper IV

Mill evaluation of an intensified mechanical pulping process

Christer Sandberg, Jan-Erik Berg and Per Engstrand

Nordic Pulp & Paper Research Journal, 2017, 32(2), 204-210.

Paper V

Development of fibre properties in mill scale high and low consistency refining of thermomechanical pulp (Part 1)

Rita Ferritsius, Christer Sandberg, Olof Ferritsius, Mats Rundlöf, Geoffrey Daniel, Kathrine Mörseburg and Dinesh Fernando

Nordic Pulp & Paper Research Journal, 2020, 35(4), 589-599.

Paper VI

Fibre development in an intensified mechanical pulping process

Christer Sandberg

Holzforschung, 2021, 75(9), 824–837.

Paper VII

New centre-plate design improves DD refiner performance

Christer Sandberg, Mikael Lundfors and Karl Lönngren

International Mechanical Pulping Conference, Vancouver, Canada, 2022, 63-68.

Author contributions

The author contributions to the papers included in this thesis are as follows:

Paper I

The idea and planning of the study, interpretation of the results and writing the paper together with the co-authors.

Paper II

The idea and planning of the study, performing trials, interpretation of the results and writing the paper together with the co-authors.

Paper III

The idea and planning of the study, performing trials, interpretation of the results and writing the paper together with the co-authors.

Paper IV

The idea and planning of the study, performing trials, interpretation of the results and writing the paper together with the co-authors.

Paper V

All parts of the study, including: planning, performing trials, interpretation of the results and writing the paper were made together with the co-authors.

Paper VI

The idea and planning of the study, performing trials, interpretation of the results and writing the paper.

Paper VII

Planning of the study together with the co-authors, performing trials, interpretation of the results and writing the paper together with the co-authors.

Related material

The effect of process design on refiner pulp quality control performance
Sund, J., Sandberg, C., Karlström, A. Thungström, G. and Engstrand, E.
Nordic Pulp Paper Research Journal, 2021, 36(4), 594-607.

Energy efficiency in mechanical pulping – definitions and considerations
Sandberg, C., Ferritsius, O. and Ferritsius, R.
Nordic Pulp Paper Research Journal, 2021, 36(3), 425-434.

On the development of the mechanical pulping process - a review
Sandberg, C., Hill, J. and Jackson, M.
Nordic Pulp Paper Research Journal, 2020, 35(1), 1-17.

Process intensification in mechanical pulping
Sandberg, C., Berg, J.-E. and Engstrand, P.
Nordic Pulp Paper Research Journal, 2017, 32(4), 615-622.

Theoretical analysis of LC-refining - pressure screening systems in TMP
Rubiano Berna, J. E., Sandberg, C., Martinez, M. and Olson, J.
Nordic Pulp Paper Research Journal, 2019, 34(1), 46–58.

Low dosage sulfite pretreatment at different temperatures in mill scale TMP production
Nelsson, E., Paulsson, M., Sandberg, C., Svensson-Rundlöf E. and Engstrand, P.
Nordic Pulp Paper Res. J, 2017, 32(1), 59-69.

Low dosage sulfite pretreatment in a modern TMP-line
Nelsson, E., Sandberg, C., Svensson-Rundlöf, E., Engstrand, P., Fernando, D. and Daniel G.
Nordic Pulp Paper Research Journal, 2015, 30(4), 591-598.

Comparison of mechanical pulps from two stage HC single disc and HC double disc – LC refining
Andersson, S., Sandberg, C. and Engstrand P.
Appita journal 2012, 65(1), 57-62.

Effect of flow recirculation on pulp quality and energy efficiency in low consistency refining of mechanical pulp
Sandberg, C. and Berg, J.-E.
Nordic Pulp Paper Research Journal, 2015, 30(2), 230-233.

Low-consistency refining of mechanical pulp in the light of forces on fibres.
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Potential of low consistency refining of TMP – Mill evaluation. Int. Mech. Pulping
Sandberg, C., Sundström L. and Nilsson, L.
International Mechanical Pulping Conf. Sundsvall, Sweden, 2009, 186-189.

New TMP-line improves pulp quality and reduces energy consumption
Sandberg, C., Sundström, L., Andersson S. and Nelsson, E.
International Mechanical Pulping Conf. Xian, China, 2011, 472-475.

Increased energy efficiency in TMP production through fractionation in hydrocyclones
Sandberg, C., Sundström L. and Nilsson L.
International Mechanical Pulping Conf. Helsinki, Finland, 2001, 425-431.

Fibre fractionation - a way to improve paper quality
Sandberg, C., Nilsson, L. and Nikko, A.
International Mechanical Pulping Conf. Stockholm, Sweden, 1997, 167-171.

List of abbreviations

The abbreviations used denoting process configurations are explained in section 7.1.

adt	Air-dry ton (900 kg absolute dry pulp)
BAT	Best available technology
BDDJ	Britt Dynamic Drainage Jar (fibre and fines separator)
BMcN	Bauer McNett (fibre size fractionator)
CD	Conical disc (refiner)
CD	Cross direction (paper)
CPT	Chip pretreatment
CSF	Canadian Standard Freeness
CTMP	Chemithermomechanical pulp
DCS	Distributed control system
D/IF	Delamination, internal fibrillation
DIP	Deinked pulp (produced from recycled paper)
DD	Double disc (refiner)
FL	FiberLab (fibre analyzer)
GCC	Ground calcium carbonate (mineral filler in paper)
HC	High consistency (normally referring to a dry content over 30%)
kWh	Kilowatt hours
LC	Low consistency (normally referring to a dry content below 6%)
l.w.	Length-weighted (average fibre length)
l.l.w	Length-length-weighted (average fibre length)
MC	Medium consistency (normally referring to a dry content of 7-15%)
MD	Machine direction (paper)
p	Pressure
P	Primary wall (outermost layer of the fibre wall)
PE	PulpEye (fibre analyzer)
PM	Paper machine
PRMP	Pressurized refiner mechanical pulp
R-K	Rapid-Köthen (semi-automatic laboratory paper sheet former)
RMP	Refiner mechanical pulp
RTS	Retention time, Temperature, Speed (A high speed refiner)
S1	Outermost layer of the secondary fibre wall
S2	Second and thickest layer in the secondary fibre wall
SEM	Scanning electron microscope
SD	Single disc (refiner)
SGW	Stone groundwood (pulp produced by pressing logs against a rotating cylinder with a grinding surface)
SRE	Specific refining energy
t	ton (1000 kg)
TEA	Tensile energy absorption
TMP	Thermomechanical pulp

Greek letters

Δ	Difference, *e.g*. pressure
η	Energy efficiency

1 Introduction

1.1 Background

The purpose of this work is to show that it is possible to reduce the production cost for mechanical pulps through increased energy efficiency and new process designs that require less equipment. The focus is on processes based on refiners, with wood chips as raw material.

Wood fibres are used to produce papers within a large spectrum of physical properties in terms of strength, bulk, opacity, brightness, surface smoothness and stiffness adapted for a multitude of end-uses covering the range from toilet paper to high strength sack paper and luxury packaging. The main factors affecting the properties of wood pulps are:

- The wood quality (species, part of stem used, growth rate, etc.)
- The degree of chemical treatment in the fibre separation and bleaching processes
- The level of mechanical treatment, for example refining

Depending on the degree of chemical treatment in the fibre separation process, pulps are often classified in four major classes with increasing application of chemicals: mechanical, chemimechanical, semi-chemical and chemical pulps, with a successive transition between the pulp types. Chemical pulps have the widest span of applications due to their higher strength and higher achievable brightness. Mechanical pulps have sufficient strength, high light scattering, high bulk as well as good surface smoothness which, in most cases, makes them more suitable for low grammage printing paper than chemical pulps. Chemimechanical pulps are mainly used for paper board due to high bulk and low shive content but also for other grades such as printing and writing as well as tissue.

Mechanical pulp is produced with two techniques, by grinding of whole logs against an abrasive cylinder, referred to as stone groundwood (SGW) and by the milling of wood chips between rotating metal discs in machines called refiners. The refiner process requires high specific electrical energy to separate and develop the fibres to a pulp intended for printing paper. Today, many processes require over 2000 kWh/t refining energy plus 200-300 kWh/t of auxiliary energy (pumps, agitators, screw conveyors, screens, presses, etc.). At present, around 1.2 million tons of mechanical pulp for printing paper is produced annually in Sweden, requiring approximately 3 TWh of electrical energy. The production of chemimechanical pulps amounts to 1.3 million ton per year.

The demand for printing paper is declining steadily, but there will likely still be a need for printing paper also in the future, however at a lower level. Due to the declining market, few new production lines for printing paper have been built during the last decade and the existing lines are in many cases operating with old equipment with low energy efficiency. Therefore, there is clearly a need to upgrade the processes to increase the energy efficiency, improve automation and reduce maintenance costs. There are, however, new areas of applications emerging for mechanical pulps. Holmen Paper has introduced a new growing portfolio of products for containerboard based on 100% mechanical pulp. Moreover, the production of chemithermo-mechanical pulp (CTMP), which is produced in a similar process, is increasing in Sweden and globally, mainly in integrated paperboard mills. The CTMP process generally requires less energy compared to TMP, but there is certainly a potential to improve the efficiency even for CTMP production.

During the last two decades of the 20th century, the chemical processing industry underwent a transformation. The process development changed from being unit operation focused to function focused. The result is more compact processes with less equipment, higher yield and lower energy demand. When the development is made in an innovative way with large effects on process performance, it is referred to as process intensification (Stankiewicz and Moulijn 2002). My work is inspired by the concepts of process intensification, especially the striving for more compact processes with higher efficiency (Sandberg *et al.* 2017).

In this work, I have studied how a mechanical pulping process can be designed to reduce the number of unit operations and how simplified process concepts affect pulp quality and the specific electrical energy demand.

1.2 Outline of the thesis

The **first chapter** provides a background to the work and presents the goals and research approach. **Chapter 2** describes the principles of mechanical pulping. In **chapter 3**, the most important properties of mechanical pulps related to this work are described. The historical development and the most important unit operations in the mechanical pulping process are described in **chapter 4**. The knowledge gap that this work addresses is discussed in **chapter 5**. In **chapter 6**, methods and pulp and paper analyses are listed. **Chapter 7** contains a brief description of mill trials. The results of the investigations are presented and discussed in **chapter 8**. **Chapter 9** contains concluding remarks and the conclusions are summarized in **chapter 10**. Finally, suggestions for further work are made in **chapter 11**.

1.3 Research method

This research has been performed exclusively in mill scale operations in Sweden over a relatively long period spanning almost ten years, mainly in the Holmen Braviken mill and, to some extent, the Holmen Hallsta mill and the Stora Enso Kvarnsveden mill. Over the years, re-piping, restructuring and new investments, especially in the Braviken mill, have made it possible to study a large number of process configurations. Step by step, the processes have been changed and pulp quality and energy efficiency assessed with the target to reduce the specific energy and the number of unit operations. In all of these studies, the pulp quality has been assessed by optical fibre analyses and handsheet-testing for standard properties such as tensile index and light scattering coefficient. In two studies (Papers V and VI) more detailed fibre analyses were carried out to retrieve more detailed information on how process conditions affect the pulp quality at the fibre level and in two additional studies (Papers III and IV), the pulp production processes were evaluated on paper machines and in printing presses.

This way of doing research has pros and cons:

- There are limitations on how extensive modifications can be made due to the fact that the produced pulp must be good enough to make paper.
- It is costly to make modifications in full scale production lines.
- A big advantage is that, if the produced pulp can be used on a paper machine without runnability problems and subsequently be printed with sufficient quality, there is no better proof of concept when a new process design is evaluated.

A unique contribution of this work to the mechanical pulping research, is that a large number of process combinations have been investigated with mill scale equipment with similar raw material (Norway spruce) and evaluated in the same laboratory. In two of the investigations, Papers V and VI, all pulps were evaluated in additional labs to increase the reliability of the results.

The studies constituting this thesis are not presented in a chronological order, but rather based on a successive process design development. The focus has been on developing the whole process and to understand synergies and limitations of combined unit operations rather than optimizing a specific unit operation.

1.4 Purpose

The purpose of this work is to reduce the production cost for mechanical pulps.

The means utilized to this end, were to reduce the specific electrical energy demand and the number of unit operations needed to produce the required mechanical pulp.

The prerequisites were to maintain acceptable paper quality as well as runnability on the paper machines and in the printing presses.

Research question (see also chapter 5)

How should a process for mechanical pulp production be designed and operated to increase the energy efficiency and to attain sufficiently developed fibres and fines with a reduced number of unit operations?

The approach was to improve the main line refining configuration and refining conditions to eliminate additional fibre development and shive reduction, thereby avoiding the requirement for screening and rejects treatment.

1.5 Scope and limitations

This work is focused on mechanical pulp produced in refiners, intended for printing paper using Norway spruce (*Picea abies*) as raw material. However, the approach can potentially be utilized for the development of other mechanical pulp production processes, such as chemimechanical pulp for paperboard and also with other raw materials *e.g.*, pine species or hardwoods. Only those refiners available in the Braviken, Hallsta and Kvarnsveden mills have been utilized. Of course, there might be other processes that could be more efficient, but these three mills incorporate all major types of available refiners and other advanced fibre processing equipment, such as compressive chip pretreatment and fibre fractionation systems.

The pulps produced in this work are mainly intended for use in uncoated paper grades printed by the offset, coldset and heatset printing processes. In all studies, the performance of the pulps has been assessed with lab measurements. However, in two studies (Papers III, IV), the produced pulps were evaluated on paper machines as well as in printing presses. In all of these studies, the pulp quality has been related to the specific refining energy required and, in some cases, the auxiliary energy used in the operation of pumps, agitators, presses, etc. has been considered.

A prerequisite has been that the brightness of the produced pulps should be maintained at around 60% ISO. Only low amounts of sodium dithionite have been added for bleaching and in these cases the dithionite was added to the latency chest or to the final pulps. The only optical property that has been explicitly studied in this work is the light scattering coefficient. The effects of white water circulations, bleaching and other paper making components, such as starch and mineral fillers, have not been studied.

Over time, a large number of process designs that are presented in the papers constituting this work and the related papers have been investigated. However, some of these processes are not included here since they do not contribute to both aims of the thesis: to simplify the process and increase the energy efficiency for mechanical pulping.

Since the mill scale trials and new process designs have been performed over several years, there are of course changes over time, such as varying raw material properties, that can affect the results. However, the raw material has all the time been Norway spruce with a ratio of roundwood and sawmill chips of 70/30 in most studies.

2 Principles of mechanical pulping

This chapter describes the constitution and mechanical behaviour of wood and gives an introduction to mechanical pulping.

2.1 Graphical papers

Paper used for printed products, such as newspapers, direct mail, catalogues, books, etc. must have some distinct properties. The most important is the ability to convey text and images to the end-user at a quality level decided by the producer. The visual appearance of paper is affected both by optical properties, such as brightness and opacity as well as the surface structure which all depend on the physical and chemical structure of the paper. The paper must also have certain mechanical properties, *e.g.*, bending stiffness and tensile strength, to withstand the relatively high forces experienced in the paper machines and printing presses and also to provide an intended feeling when handled by the end-user. Of course, the demands differ for a paperback book paper and a magazine paper, but still, it is mainly these aspects that are important. The distinguishing properties of mechanical pulps are presented in chapter 3.

The visual appearance and the mechanical properties of paper are affected by the sheet structure in a complex way. Paper is constructed from pulp (wood components: fibres, fines, extractives), mineral fillers and added performance chemicals. The paper quality is not only affected by the selection of these raw materials, but also by the production process (type of machinery, combination of unit operations and process conditions). This means that a certain paper quality can be produced with a multitude of process combinations which will affect both investment and variable costs.

The mechanical separation of wood fibres from chips renders fibres that are relatively short and stiff compared to chemical pulp fibres and also creates a large proportion (30-40%) of smaller fibrous particles referred to as fines. This composition gives mechanical pulps their distinguishing characteristic of high opacity at a given strength as well as high surface smoothness, which in most cases makes them better suited for low grammage printing paper than chemical pulps. The high stiffness of mechanical pulp fibres compared to chemical pulp fibres also makes them suitable for use in the middle layers of paperboard.

Drawbacks of mechanical pulps in comparison to chemical pulps are that the maximum achievable brightness is lower, the brightness is not stable when exposed to light and strength properties are lower. Another drawback is that high specific electrical energy is required to reach a given strength, but on the other hand, the yield is high, normally above 96% for unbleached TMP (Holmbom *et al.* 2005), and thereby the wood consumption is much lower than for chemical pulp.

2.2 The raw material

In the Nordic region the most common raw material for mechanical and chemimechanical pulps is Norway spruce (*Picea abies*). In other parts of the world other softwood and also hardwood species are used. In this work only mechanical pulp made from Norway spruce is considered.

2.2.1 Wood morphology

Wood is a heterogeneous material with a complex structure. The main constituents of the tree stem are the tracheids, long and thin cells usually referred to as fibres, that support the tree and transport water and nutrients from the roots. In northern softwoods (conifers), the fibres formed during the growing season have a variation in morphology, which is mainly reflected in the fibre wall thickness and fibre perimeter, Figure 1. During the early stage of the growing season, fibres are thin-walled with large perimeters and are referred to as "earlywood fibres". Towards the end of the growing season, the fibres are more thick-walled with smaller perimeters and are referred to as "latewood fibres". The intermediate fibres between earlywood and latewood with relatively large perimeter and rather thick walls are often referred to as "transition wood fibres".

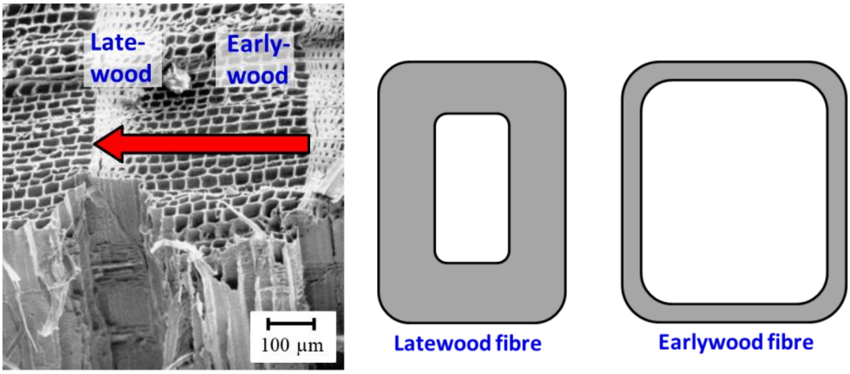

Figure 1. To the **left:** A cross-section of wood showing annual rings with early- and latewood. The arrow shows one annual ring and the direction of growth. To the **right**: A schematic illustration of latewood and earlywood fibres.

Due to the large difference in cross-sectional dimensions, earlywood and latewood fibres have different paper making potential (Paavilainen 1992, Retulainen 1993, Seth *et al.* 1997). Thick-walled fibres, especially transition-wood fibres, have a negative effect on print quality due to their poor conformability and tendency to expand or swell in the printing process (Kartovaara 1990, Lee *et al.* 1993, Antoine *et al.* 1995, Norman and Höglund 2003). Thick-walled fibres located close to the paper surface, as shown in Figure 2, can be especially problematic.

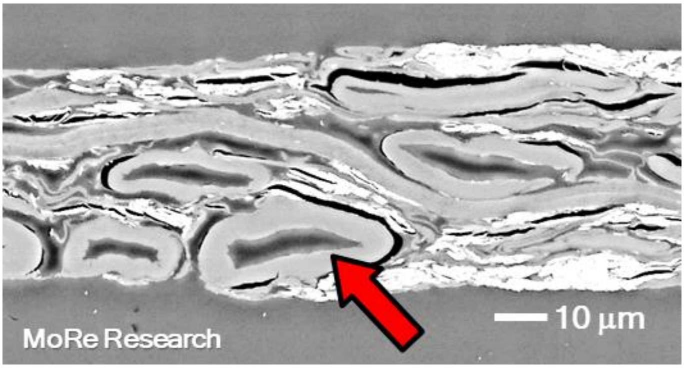

Figure 2. Cross-section of a magazine paper from Holmen Paper. Thick-walled fibres (red arrow) in the surface can be detrimental for print quality.

The fibres have a layered fibrillar micro-structure with varying chemical composition and fibrillar orientation in each layer, Figure 3. The fibres are embedded in an amorphous matrix with a high content of lignin, the middle lamella, shown in black in Figure 3. The transition between the primary wall and the middle lamella is often difficult to detect in lignified fibres and therefore they are together usually referred to as the compound middle lamella. Spruce wood, excluding the bark, has an average chemical composition of 30% lignin, 44% cellulose, 21% hemicelluloses and 2% extractives. The content of lignin increases towards the middle lamella. For more detailed information on the wood ultrastructure of spruce, see *e.g.*, Brändström (2002).

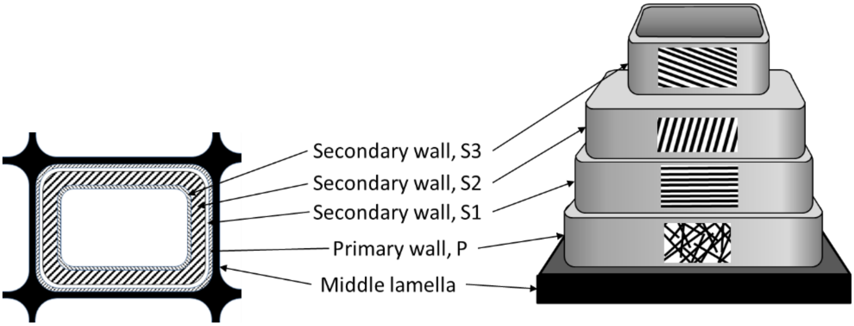

Figure 3. Schematic structure of the fibre wall, not in scale, based on Brändström (2002). To the **left:** Cross-section of a fibre in wood, showing the layered cell wall structure and middle lamella (black). To the **right:** The approximate fibrillar orientation in the cell wall layers.

2.2.2 Wood softening

Wood can be described as a material with both viscoelastic and plastic behaviour (Schniewind and Barrett 1972, Salmén and Fellers 1982). The mechanical behaviour of a viscoelastic material subjected to loading depends on temperature and deformation rate (strain rate) (McCrum *et al.* 1967). Increased temperature makes viscoelastic materials act softer and increased deformation rate makes them act stiffer. The major wood components, cellulose, hemicelluloses and lignin are softened by increased temperature and moisture in various degrees (Goring 1963). Above room temperature, the viscoelastic properties of water-saturated wood are mainly affected by the lignin. The softening increases gradually, but the highest rate of increase is in the interval 60-90°C at low deformation rate. The interval is shifted towards higher temperature at higher deformation rate (Becker *et al.* 1977, Irvine 1985).

The temperature of wood affects how fibres are separated when loaded to fracture. At a temperature in the lower part the softening interval, a large share of the fibres are broken across the fibre direction and fibre separation occurs predominantly in the secondary cell wall layer of the fibres. At a temperature in the upper part of the softening interval, fibre separation occurs closer to the middle lamella and fewer fibres are broken across the fibre direction (Koran 1967, Koran 1968, Berg 2001).

2.2.3 Deformation and deformation rate

In mechanical pulping equipment (refiners and grinders), wood is cyclically loaded and deformed until the structure is disintegrated. The deformation rate, also called strain rate, is defined as loading velocity divided by original size of a loaded specimen. Wood material that behaves in a soft and pliable manner at lower deformation rates will act stiffer and more brittle at higher deformation rates (Becker *et al.* 1977, Irvine 1985, Widehammar 2004). However, wood compression experiments carried out at high temperature (100°C) and at different strain rates indicate that the strain rate dependence may be smaller than expected at higher temperatures (Moilanen *et al.* 2017).

The viscoelastic properties of wood have been studied by causing specimens to oscillate with small amplitudes (*e.g.*, Atack 1972, Becker *et al.* 1977, Salmén 1984). The oscillation frequency in such studies can be associated to deformation rate only if the degree of deformation is known. In a refiner, it is difficult to measure the deformation rate since it is not known how much material is present in each treatment position. However, the refining conditions will certainly affect the deformation rate and will therefore, together with the wood softening, affect the pulp quality. The effect of refining conditions on fibre separation and development is discussed further below.

For printing papers, relatively large plastic deformations of the fibres are needed to make them conformable. Uhmeier and Salmén (1996) showed that, for a given amount of applied energy, larger permanent plastic deformation is attained if wood is treated with a low number of loading cycles with a high degree of deformation compared to a large number of loading cycles with a low degree of deformation. In a refiner, the former would likely be attained if the residence time in the refining zone and the disc gap is reduced. However, an excessive degree of deformation can lead to fibre length reduction. This balance between efficient energy transfer and maintained fibre dimensions implies that fatigue plays a certain role in the fibre development process (Salmén 1984, Hamad and Provan 1995, Salmi *et al.* 2012). On the other hand, Moilanen *et al.* (2017) showed that wood should be subjected to large single compressions to attain a high efficiency of internal fibrillation.

2.2.4 Chemical modifications of wood and fibres

Wood is a very complex polymeric material that is affected not only by moisture and heat (section 2.2.2) but also by the chemical environment and chemical treatments. The reactivity of the wood polymers can be used to change the properties of wood and separated fibres within a huge range, from production of crystalline nanocellulose with a wood yield of around 25% to low dosage chemical treatments of mechanical pulps that improve tensile index and reduce the shive content but have a negligible effect on wood yield. The subject of chemical modifications of wood is enormous and can only be considered briefly here with focus on relatively mild treatments used in mechanical pulping. In the present work, sodium sulphite is the only chemical that has been used.

By far, the most common chemical treatments used in mechanical pulping (wood yields >90%) are based on sodium hydroxide, sodium sulphite and/or hydrogen peroxide. Mild treatments of wood or mechanical pulp change the polymer structure and interactions between the wood polymers in a complex way (Stevanic-Srndovic and Salmén 2008). The effect of chemicals on pulp properties depends on the treatment conditions, such as chemical charge, pH, concentration, reaction time and temperature.

It is known that sodium sulphite and alkaline hydrogen peroxide treatments of wood or fibres increases the number of charged groups in the treated material, mainly as sulphonate and carboxylic groups in the lignin and carboxylic groups in the hemicelluloses (*e.g.*, Gellerstedt *et al.* 1977, Beatson *et al.* 1984, Engstrand *et al.* 1991, Konn *et al.* 2007, Chang *et al.* 2010). Moreover, sulphite treatment of lignin model compounds show that beta-aryl-ether bonds are cleaved which could indicate that the degree of crosslinking in lignin is reduced (Gellerstedt *et al.* 1977). On the other hand, exposure of the wood or fibres to high temperatures under long time, with or without chemicals present, can lead to increased crosslinking of the wood polymers and thereby to stiffer fibres (Ölander *et al.* 1990).

Depending on the temperature, pH and ionic strength in the system, the increased number of charged groups may cause electrolytic swelling of the fibre wall (Katz *et al.* 1981, Broderik *et al.* 1996, Fjellström *et al.* 2013). Swelling, depolymerization and increased number of charged groups can increase the fibre flexibility and bonding ability (indicated by density, Z-strength and tensile index) of the fibre material. As a result, the mentioned chemical treatments can increase the strength properties of mechanical pulps at a given specific energy, but the effect depends on the type and level of treatment. The pH at sulphite and peroxide treatments affects the density and tensile index increase, which is due to the fact that a higher pH promotes the formation of charged groups (Beath and Mihelich 1977, Katz *et al.* 1981, Moldenius 1983, Bengtsson *et al.* 1985, Stationwala 1994, Chang *et al.* 2011).

Chemical pretreatment of wood prior to refining changes the chemical structure which makes the wood softer at certain temperature and affects the separation of fibres in a manner similar to that caused by increased temperature, *i.e.*, more towards the middle lamella region (Becker *et al.* 1977, Atack *et al.* 1978, Johansson *et al.* 1997, Lai and Iwamida 1993). There are indications, that at very low doses of sodium sulphite, similar to those used in the present work, the chemical changes direct the fibre separation to the P-S1 region of the fibres (Westermark *et al.* 1987, Konn *et al.* 2007). Axelsson and Simonsson (1982) showed that chip pretreatment with a low charge of alkaline sodium sulphite, around 5-10 kg/t, can reduce the specific energy required to reach a given tensile index and light scattering coefficient. Later studies in mill scale have confirmed the reduced specific energy to a given tensile index but the light scattering coefficient was also reduced (Nelsson *et al.* 2015).

2.3 Refining

A schematic cross section of a refiner is shown in Figure 4 (left). In principle, refiners resemble the old flour mills with grooved stone discs, but the milling is made with metal discs, Figure 4 (right). The refiners are described in more detail in section 4.1. The refiner process may look uncomplicated, but at the fibre level it is very complex. However, it can be summarized in a few sentences. Wood is softened by water, heat and sometimes chemicals to a degree that it can be separated, in the right position in the wood matrix, into free fibres by applied mechanical forces. The free fibres are treated further mechanically, which makes the fibre walls flexible, develops the surface structure and creates fine material to an extent adapted to the final product. Where the correct position of fibre separation is and how much fibre development that is needed depend on what end-product the pulp is intended for.

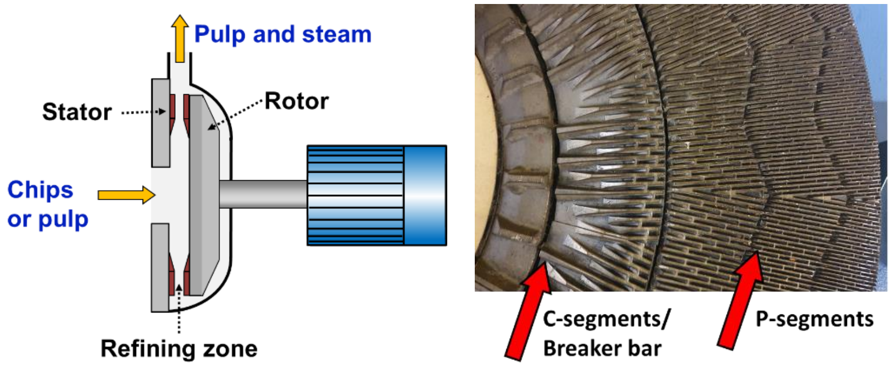

Figure 4. To the **Left:** Schematic cross-section of a single disc (SD) high consistency (HC) refiner. To the **Right**: a refiner disc for the same type of refiner.

Refining differs from other similar attrition processes, such as crushing of stone, mainly in two aspects; the sub-components of the wood, the fibres, should be maintained in a relatively intact form, not just turning the chips into wood meal (Atack 1981). Second, the wood raw material, has partly viscoelastic and plastic properties, which leads to the fact that a large share of the applied mechanical energy is inevitably dissipated as heat energy (Salmén and Fellers 1982). The specific energy required for crushing of stone to a particle size comparable to mechanical pulp is in the order of 15 – 30 kWh/t (Ballantyne *et al.* 2012, Ciężkowski *et al.* 2017) whereas for mechanical pulp production, the specific energy is two orders of magnitude higher, around 1800 kWh/t (dry pulp) for state of the art newsprint processes in Scandinavia (Ferritsius *et al.* 2014). The dissipated electrical energy transforms water into steam in the refiner and therefore water must be added to the refining to maintain the process at an adequate temperature, avoiding burning of the pulp. Thus, the pulp is blown from the refiner together with a large quantity of steam which is separated from the pulp and thereafter used for heating in the process.

It is a challenge to perform a proper fibre separation and development that is adapted to the heterogeneous wood material, since in a refiner, roughly one billion (10^9) fibres are treated per second. The refining process consists essentially of two separate processes; separation of the fibres from the wood matrix referred to as *defibration* followed by the continued mechanical treatment of the free fibres referred to as *fibrillation*. It is inevitable that these two processes of defibration and fibrillation occur, more or less simultaneously, even if there are indications that it is preferable to perform the two processes under different conditions (Salmén and Fellers 1982).

2.3.1 Defibration

Preconditioned (washed, heated and, in some cases, impregnated) wood chips are fed into the centre of the refiner, Figure 4. The rotor(s) accelerate the chips and by the centrifugal force they flow towards the breaker bar zone where they are compressed and sheared between the bars of the refiner segments to such a degree of deformation that the wood matrix is fractured, and fibres are separated. It was realized at an early stage that the defibration phase does not require much energy, not more than around 400 kWh/adt (Neill and Beath 1963), but the conditions during defibration have a large effect on the subsequent fibrillation and the attainable physical property window.

The temperature in the defibration stage affects the softening of the wood material and thereby the fibre separation, as mentioned in section 2.2.2. In non-pressurized refining (often referred to as Refiner Mechanical Pulp - RMP), fibres are broken to a large extent and separated mainly in the S2 layer which results in a pulp with low fibre length and tensile index but high light scattering. When wood is refined under pressure, the fibre separation takes place mainly in the region of the interface between the S1 and S2 layers and the pulp will have higher fibre length and tensile index, but lower light scattering compared to RMP at a certain specific energy (Atack 1972, Asplund and Bystedt 1973, Atack *et al.* 1978, Irvine 1985, Heikkurinen *et al.* 1993, Johnsen *et al.* 1995). Further increase in refining temperature changes the fibre separation to the middle lamella region and the specific energy demand to a given freeness or tensile index increases (Asplund and Bystedt 1973, Lunan *et al.* 1983, Nurminen 1999, Omholt and Miles 2008a, b).

The fibre separation is also affected by the intensity/harshness (see section 2.3.5) of the mechanical treatment during the initial refining. Increased intensity tends to affect the fibre separation in the opposite direction to increased temperature, *i.e.*, high refining intensity in the defibration stage yields pulp with more broken fibres having thinner walls and lower fibre length. Increased temperature during high intensity defibration can to some extent reduce the effects of the intensity (Kure *et al.* 2000).

Thus, it is a balance between the degree of softening and the applied mechanical forces that determines how fibres are separated and this affects their further development.

2.3.2 Fibrillation

Free fibres and fibre bundles are further treated in the refining zone equipped with more narrow bars and grooves, Figure 4 (right), and often also in subsequent refining stages. After defibration, the fibre walls are still stiff, and the fibres retain most of their original shape. For printing papers, the free fibres require more refining in order to collapse and conform and thereby contribute to a strong enough paper with appropriate printing properties (Jackson and Williams 1979, Mohlin 1980a, Corson *et al.* 2003). This further mechanical treatment of the separated fibres causes internal and external fibrillation of the fibre walls. The term internal fibrillation is often used referring to the formation of micro-cracks and delamination of the wall structure that is observed as swelling of the fibre wall and an increase in the pore volume (Karnis 1994, Hamad and Provan 1995, Lammi and Heikkurinen

1997, Moss and Heikkurinen 2003). The delamination of the cell wall finally leads to peeling of fibre wall material, thereby creating free fines particles and fibre surfaces with partly attached band or thread-like segments of the fibre wall, referred to as external fibrillation, Figure 5.

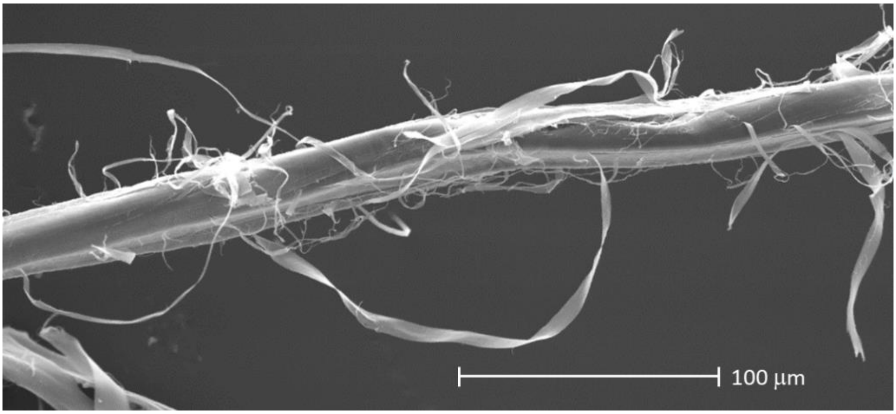

Figure 5. SEM picture of a fibre from an RGP68DD refiner displaying high external fibrillation. Where some of the fibrils have been loosened, it can be seen, from the angle of the fibrillar structure to the fibre axis, that the fibrils originate from the S2 layer. Picture by Dinesh Fernando, SLU, Uppsala, Sweden.

The internal fibrillation and the reduced fibre wall thickness makes the fibres more flexible and susceptible to collapse. The increased fibre flexibility and creation of fines contribute to increased paper density and tensile strength (Mohlin 1977, Broderick *et al.* 1996, Jang *et al.* 1996).

2.3.3 Fibre breakage

During both defibration and fibrillation, fibres can be exposed to such high strain levels that the tubular cell structure is destroyed. The rupture can occur across the fibre which creates smaller pieces of fibres and thereby reduces fibre length, or the fibre wall can break along the spiral structure of the S2 layer which is referred to as fibre splitting. Fibre splitting occurs mostly in the defibration phase and mainly for thin-walled earlywood fibres and can lead to a total unravelling of the fibre to a long ribbon or band-like sheet. (Reme *et al.* 1998, Pöhler and Heikkurinen 2003)

2.3.4 Fines generation

During the defibration and fibrillation processes, small wood cells (ray cells) are separated from the wood and small fragments are created both from the compound middle lamella and by successive peeling of secondary fibre walls, Figure 6. These morphologically different particles are, independent of the relative proportions, referred to collectively as "fines". All fibre types are peeled, at least to some extent, but peeling occurs predominantly on thick-walled (latewood) fibres, whereas thin-walled fibres are more broken and axially split (Johnsen *et al.* 1995, Mohlin 1997, Reme *et al.* 1999). The fines fraction contributes to structural, mechanical and optical sheet properties, such as surface smoothness, density, tensile strength and light scattering, and is therefore important for the unique properties of mechanical pulp (*e.g.*, Marton 1964, Giertz 1973, Retulainen *et al.* 1993, Johnsen *et al.* 1995). During the initial phase of refining, the created fines are predominantly broken ray cells and flake-like pieces originating mainly from the compound middle-lamella, together often referred to as primary fines, while upon further refining more thread-like (fibrillar) particles are peeled off from the S1 and S2 layers. Since the S2 layer is the thickest layer of the fibre, most fibrillar material originates from it for highly refined pulps. The contribution of ray cells to sheet strength is negligible and that of fibrillar fines is very high whereas the contribution of flake-like fines is in between the two extremes and relatively good (based on comparison of data from Westermark and Capreti (1988) and Luuko and Paulapuro (1999)).

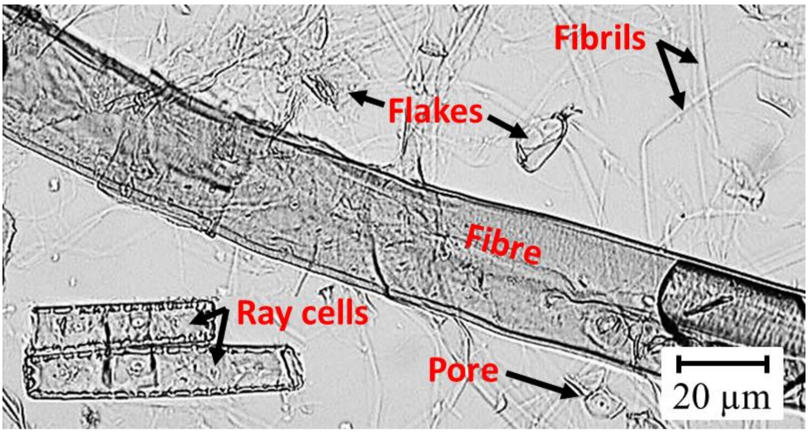

Figure 6. Light microscopy picture of an earlywood fibre and the main types of fines.

The bonding ability of released fines (indicated by handsheet tensile index) increases with increased degree of refining mainly due to the increased content of fibrillar fines (Brecht and Klemm 1953, Corson 1989, Heikkurinen and Hattula 1993, Lukko and Paulapuro 1999). Westermark and Capretti

(1988) isolated flake-like fines from a final pulp for newsprint that had a tensile index of 30.6 Nm/g which is considerably higher than that of flake-like fines isolated from a primary stage refiner, Figure 11, which has a tensile index of around 20 Nm/g (Lukko and Paulapuro 1999, Rundlöf 2002). This could indicate that also the flake-like particles develop in refining.

The character of the fines is also affected by the refining intensity. High intensity primary stage refining tends to produce larger fibrillar fines that contribute less to tensile index (Kibblewhite *et al.* 1995, Pöhler and Heikkurinen 2003, Mörseburg *et al.* 2014). However, after further refining stages, the difference seems to diminish (Pöhler and Heikkurinen 2003). At a given mass fraction of fines, smaller fines give higher contribution to light scattering and tensile index (Rundlöf 1996, Lukko and Paulapuro 1999).

In mill processes, the quality (optical and strength properties) of fines is also affected by the presence of extractives on particle surfaces (Rundlöf *et al.* 2000, Sundberg *et al.* 2000).

To summarize, refining creates a heterogenous mixture of particles of different sizes and with different properties which are affected by the refining conditions and degree of refining (applied energy). When mechanical pulps are characterized, they are often divided into three major size-fractions: long, middle and fine fractions based on laboratory screening. The long or "coarse" fraction consists mainly of intact fibres and unseparated fibre bundles (shives). The middle fraction is a mixture of cut sections of fibres and large lamellar ribbons and the fine fraction contain all the different small particles mentioned above (ray cells, flakes and fibrils) (*e.g.*, Jackson and Williams 1979). The effects of the different fractions on pulp properties are discussed in more detail in chapter 3.

2.3.5 Refining conditions

The refining is affected by several factors, such as refiner type, the feed rate of wood material and dilution water as well as the refiner pressures, applied load and segment design. These factors affect the properties of the pulp produced as well as the specific refining energy. The most important factors are described briefly below.

Pressure (temperature)

The applied energy in the refining process generates a lot of heat that is transformed into steam. The small disc gap (around 0.5 mm) restricts the steam flow, and this results in a pressure profile and consequently also a temperature profile with a maximum in the refining zone, Figure 7.

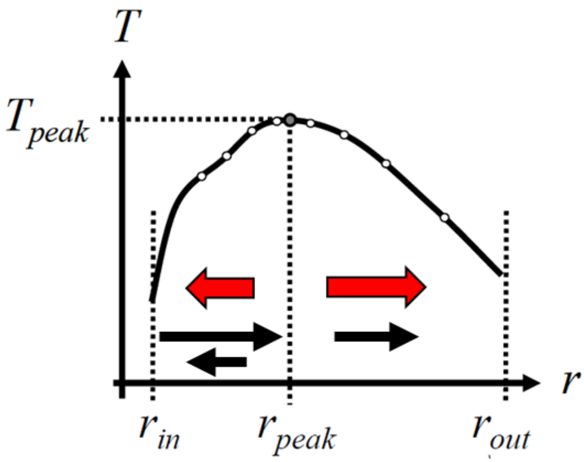

Figure 7. Example of a temperature profile along the refining zone (r = radius) of a high consistency refiner (Sikter 2007). Red arrows indicate the steam flow and the black arrows the wood/fibre flow (not shown in the original figure).

The pressure profile creates a steam flow towards the refiner inlet before the pressure peak and towards the periphery after the pressure peak. The backflowing steam leads to a mixing-zone before the pressure peak in which particles flow backwards with the steam towards the refiner inlet. After the peak, fibres flow at high velocity towards the refiner periphery with the generated steam (Atack *et al.* 1984, Härkönen *et al.* 2000).

The pressures prevailing in the refiner inlet and the refiner housing are normally controlled by valves on the blow-line and the back-flow steam line. These pressures affect the temperature that the wood and fibres are exposed to as well as the steam and fibre flow in the refining zone. Generally, a reduction in ΔP ($P_{Housing}$-P_{Inlet}) leads to smaller disc gap and thereby lower fibre length but lower specific energy to a given burst strength (Lunan *et al.* 1985). Single disc (SD) refiners are normally operated with a positive ΔP of around 50-200 kPa whereas double disc (DD) refiners are often operated close to zero ΔP or even with a small negative ΔP.

Generally, when the refiner pressure or temperature is quoted, it refers to the condition in the refiner housing, if not otherwise specified. A moderate increase in refining temperature can reduce the specific energy required to achieve a given tensile index and leads to increased fibre conformability (Höglund *et al.* 1997, Nurminen 2003, Norgren and Höglund 2009, Muhic *et al.* 2010, Fernando *et al.* 2011). The increased temperature usually enhances the formation of chromophores and thereby causes a slight reduction of brightness (Höglund *et al.* 1997, Vuorio and Bergqvist 2001, Muhic 2010). However, it has been shown that addition of a low charge of sodium sulphite eliminates the brightness loss caused by high temperature and also results in an additional increase in tensile index at given specific energy (Jackson and Åkerlund 1984, Nelsson *et al.* 2017).

Consistency

In the early refiner-based mechanical pulping processes, the pulp consistency was as low as around 8% (Eberhardt 1956). Later, it was realized that it is beneficial for the pulp properties, *e.g.*, tensile and tear strength, to have higher consistency, especially in the primary refining stage (Holzer *et al.* 1962). The non-pressurized refining made it difficult to utilize higher consistency than 15-20% in the refining due to the large steam volume. When pressurized refining was introduced, it enabled refining at much higher consistency (Charters and Ward 1973). Today, high consistency (HC) refining usually refers to operating at a blow-line consistency above 30%. The effect of consistency depends on other refining conditions such as segment design, rotational speed, production rate and motor power, but generally, higher consistency preserves fibre length, likely due to larger disc gap, and enables higher motor load (Stationwala *et al.* 1979, Murton and Duffy 2005). However, Muhic (2010) did not identify any effect of consistency in the range 32-41% for a DD refiner (RGP68DD) whereas Cort *et al.* (1991) noticed a reduction in strength properties at increased consistency for a 36 inch DD refiner operating at 1200 rpm. Therefore, at given operating conditions there is probably an optimum in consistency that differs depending on refiner type, segment design, production rate, etc. which is also indicated by the work of Alami *et al.* (1997).

Production rate

The mass flow of wood/pulp through the refiner (production rate) also affects the attained pulp properties. Within the normal operating window of a HC refiner, increased production rate requires a lower disc gap to reach the same specific energy. The reduced gap causes changes in pulp quality that depend on other refining variables such as refiner type, consistency, segment design, etc. Generally, at a given specific energy, increased production rate tends to result in pulps exhibiting increased density and tensile strength but somewhat lower tear index and in some cases, lower fibre length (Stationwala *et al.* 1979, Strand *et al.* 1993, Härkönen and Tienvieri 1995, Murton and Corson 1997).

Segment design

The segment design has a large impact on the attained pulp quality and specific energy demand. It is not possible to describe all of the work that has been made with different designs here. However, for the present work, it is relevant to emphasize the reduced residence time and thereby likely increased intensity that is attained with feeding segments, also referred to as unidirectional segments (Härkönen *et al.* 2000). Generally, coarse segments (wider and fewer bars) and feeding segments result in a similar fibre development with lower fibre length and freeness and higher light scattering at given specific energy (Kure *et al.* 2000).

Rotational speed

The rotational speed of refiners affects the refining conditions in several ways. The centrifugal force on fibres increases with the rotational speed which affects the residence time in the refining zone and thereby the forces on fibres. In countries with a 50 Hz grid, HC refiners (SD and DD) are usually operating at 1500 rpm. In some cases, SD refiners are equipped with gearboxes and operate at 2300 rpm (*e.g.*, the RTS technology from Andritz (Sabourin *et al.* 1997)). In North America, with a 60 Hz grid, larger DD refiners operate at 1200 rpm and SD refiners at 1800 rpm, which makes the difference between SD and DD less pronounced (Rodarmel et al 1990). The refining frequency, *i.e.*, the number of bar crossings per second in one position, is often referred to in the mechanical pulping literature as a variable affecting fibre development. Bar-crossing frequency in refiners should not be understood as proportional to loading velocity since bar-crossing frequency can be increased by a plate pattern with more bars and that does not increase the loading velocity, see also section 2.2.3. Sundholm *et al.* (1988) showed that increasing the frequency by increasing the number of bars on segments does not have the same effect as increasing it by increased rotational speed. Increased rotational speed certainly gives a proportional increase in loading velocity, but not necessarily in deformation rate since, at a given disc gap, the amount of wood/fibres between the bars is probably reduced at the same time, which affects the deformation rate in the opposite direction. It is not known in detail how process conditions affect the deformation rate and degree of deformation in a refiner. However, a general description can be made. The degree of deformation of the wood material will primarily depend on disc gap as well as the amount of material in bar crossings and the deformation rate also depends on rotational speed. How much material that is captured in each bar crossing is difficult to measure, but will depend on several factors including segment design, disc gap, production rate, differential pressure, Δp (housing pressure – feed pressure), rotational speed, fibre length distributions, chemical environment, etc.

Refining intensity

It is generally accepted that for a certain amount of applied specific energy in a refiner, the properties of the produced pulp can vary within a wide range depending on how the energy is applied. The "*how*" has been represented by a term referred to as "intensity" which is intended to describe the harshness of the refining treatment. Refining intensity is a complex property that has been discussed over the years and there is still no clear definition of it. Miles (1990) proposed that refining intensity is defined as specific energy divided by either pulp residence time or number of impacts. However, many questionable assumptions were used to calculate pulp residence time, as has been pointed out by *e.g.*, Murton and Duffy (2005) and Engberg and Berg (2011).

Kerekes (2011) proposed that the forces acting on fibres is a more adequate measure of intensity. It is actually the forces and strains on fibres that cause the fibre development rather than the consumed energy. The force on a fibre calculated by Kerekes is an average value over the entire segment surface. Karlström and co-workers used an extended entropy model to calculate average forces on bars as a function of radius in a refiner (Karlström *et al.* 2008, Karlström and Eriksson 2014).

Refining with feeding or coarse segments or increased rotational speed usually results in reduced specific energy demand to a given tensile index as well as pulps with lower fibre length and higher light scattering (Sundholm *et al.* 1988, Cort *et al.* 1991, Miles *et al.* 1991, Heikkurinen *et al.* 1993, Høydahl *et al.* 1995, Nurminen 1999, Kure *et al.* 2000, Muhić *et al.* 2011). These refining conditions are often considered to increase refining intensity which is an interpretation that will be used in this work.

Increased wood softening by increased refining temperature might, at least to some extent, counteract the effect of increased refining intensity. The combination of increased refining temperature and rotational speed, which is the basis of the RTS process, can reduce the refining energy by more than 20% compared to normal SD refining, at maintained strength and optical properties (Sabourin *et al.* 1997; Nurminen 1999, Wahlgren *et al.* 2004). Fibre properties differ, however, from normal TMP. Pulp produced at higher intensity has fibres with thinner fibre walls and a higher proportion of axial splits in the walls (Kure and Dahlqvist 1998, Murton *et al.* 2002, Pöhler and Heikkurinen 2003).

3 Physical properties of mechanical pulps

This chapter gives a brief overview of some important properties of mechanical pulps for printing paper. In chapter 6, the properties studied in this work are presented.

3.1 Mechanical pulp characteristics

The degree of chemical and mechanical treatments in the production of pulp has a large effect on the multidimensional property space of the produced pulp. Mechanical pulps have a high opacity at sufficient strength and brightness which makes them suitable for printing papers of low basis weight Moreover, mechanical pulps have high bulk which render paper with high bending stiffness at a given basis weight. These paper properties are an effect of stiff fibrous material (fibres, middle fraction and fines) and a large fines fraction, and also bulkier fines, that results in higher light scattering relative to bonding in comparison to fines from chemical pulps. The high light scattering ability of the paper structure rendered by mechanical pulps is crucial for the performance. A higher light scattering coefficient increases both the light reflected by the paper, measured as *e.g.*, brightness, and the opacity.

Due to the lower conformability, the bulky smaller particles also contribute to the high surface smoothness at a given density for papers based on mechanical pulp. Stiff mechanical pulp fibres contribute to a bulky sheet structure, which is utilized for example in the construction of folding boxboard (FBB). However, for printing papers, too stiff fibres will not conform in the sheet resulting in low surface smoothness, low strength properties and poor print quality. (*e.g.*, Jackson and Williams 1979, Corson 1980, Mohlin 1980a, Retulainen *et al.* 1993, Antoine *et al.* 1995). Conformable long fibres are especially important for high quality printing papers, such as SC and LWC papers (Kure et al. 1999a). Thus, the key is that the mechanical treatment (refining) of the wood and fibres simultaneously develops the fibre conformability and surface structure as well as generates the fines essential for the properties of mechanical pulps.

The different character of chemical and mechanical pulps is often illustrated in the two-dimensional plot of light scattering coefficient and tensile index as shown in Figure 8.

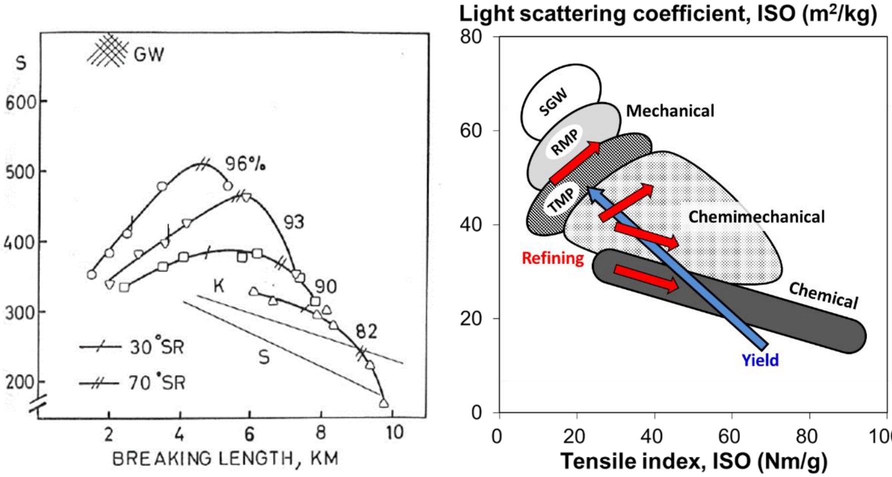

Figure 8. The degree of chemical treatment (yield) affects how the light scattering coefficient, *s*, develops with refining (increased tensile index or breaking length). To the **Left:** Comparison of ground wood pulp, chemimechanical pulps with different yields and two chemical pulps (sulphite and kraft) (Giertz 1968). To the **Right:** Similar illustration redrawn from Höglund (1977) with the effect of degree of chemical treatment (yield) and refining shown by the blue and red arrows respectively.

For mechanical pulps (high yield), the light scattering coefficient increases with increased degree of refining. With decreasing pulp yield, the increase in the light scattering coefficient becomes lower with the degree of refining and finally, for chemical pulps, the light scattering coefficient decreases with increased refining.

Other unique characteristics of mechanical and chemimechanical pulps are their higher bulk and stiffness at a given tensile strength compared to chemical pulps, Figure 9.

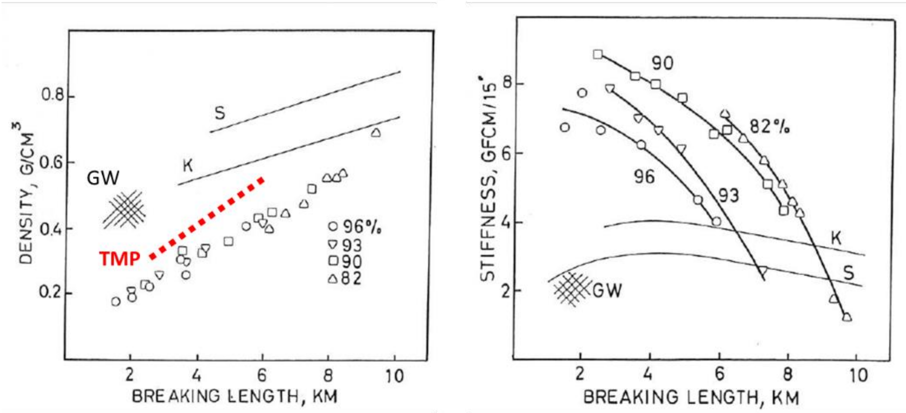

Figure 9. At a given breaking length, the chemimechanical refiner-pulps render sheets with lower density (**left**) and higher stiffness (**right**) than chemical pulps (Giertz 1968). In the left figure, a dashed line representing average data on ISO handsheets prepared from different TMP pulps is included for comparison (recalculated data from Ferritsius *et al.* 2014).

3.2 Optical properties

The visual appearance of a printed paper depends on many paper properties and it is, in the end, a subjective experience for the person looking at it. The appearance depends on the spectral distribution and intensity of light reflected by the material in different directions, which is affected by both how light is scattered and absorbed. The reflectance can be measured as reflectance factors over the visible spectrum and expressed as functions of the ratio of the light scattering coefficient, *s*, and the light absorption coefficient, *k*, using the Kubelka-Munk model. Optical properties, such as brightness, opacity and whiteness, are usually expressed as single values calculated by applying filter weights to reflectance factors for a specified wavelength range. (Pauler 2012)

Printing papers have given targets for optical properties that depend on both *s* and *k* which are affected by the conditions of the mechanical treatment. The light scattering coefficient is related to the sheet structure which is affected by the particle size distribution and fibre wall structure. If particle surfaces are very close or bonded to each other, less area is available for light scattering and thus decreasing the light scattering coefficient. This is the reason for the lower contribution to *s* by chemical pulp fines compared to mechanical pulp fines (Luukko *et al.* 1999). The *k* value is related to chemical structures (chromophores), mainly present in the lignin, that absorb light. Chromophores are present in native wood to different degrees depending on species but can also be created during the processing of chips and pulp.

Chromophores are created when wood and pulp are exposed to oxygen, light and high temperature, especially if transition metals, *e.g.*, iron, are present (Gellerstedt 2009). The k value can be reduced by chemical treatments, *e.g.*, sulphite, dithionite or peroxide. Since the brightness depends on the ratio of s and k, for an increase in k, the brightness can to some extent be maintained by an increase in s.

The fines fraction has a large effect on the light scattering of mechanical pulps, but the properties of the fibre fraction (size distribution, internal and external fibrillation, etc.) sets the level, Figure 10, (Corson 1980, Lindholm 1983, Rundlöf *et al.* 1995).

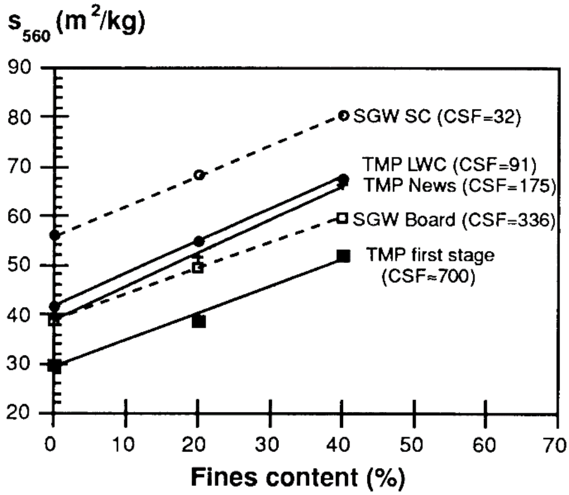

Figure 10. The light scattering coefficient increases linearly with addition of fines from respective pulp for both coarse and highly refined fibres. Primary fines and fines from highly refined pulps give similar slopes. At a given fines content, the light scattering coefficient of the pulp is determined by the light scattering of the fibre fraction. Figure from Rundlöf *et al.* (1995).

It is mainly the amount of fines rather than the character of the fines (ratio of flake-like and fibrillar particles) that affects the light scattering, but also the particle size has an effect. The smallest fines yield the highest increase in scattering at a given addition (Rundlöf 1996).

Almost all printing paper qualities contain mineral fillers, for example GCC (ground calcium carbonate), that are used to improve print quality and optical properties such as opacity, through an increase in the light scattering coefficient. In this current work, the effect of fillers has not been studied but it is briefly discussed in chapter 9.

3.3 Mechanical properties

The strength of a paper web is important for runnability, both on paper machines and in printing presses. In older literature, much focus was put on wet-web tensile strength due to the open draws in the paper machines at the time as well as on tear strength. High tear strength seemed to reduce, at least to some extent, the effect of shives on web breaks (Braviken mill experience). Since modern paper machines do not have open draws and TMP lines have barrier screens nowadays, wet-web tensile strength and tear strength are of less importance. The experience from the Braviken mill is that tensile index and strain-at-break are more important for runnability of offset papers. There are, of course, other factors that affect runnability that must be considered.

The tensile strength of mechanical pulps depends on the bonding ability of all fractions of the pulp. Development of the fractions larger than fines have a stronger influence on the achievable level of tensile index than on the light scattering coefficient, Figure 11, (*e.g.*, Mohlin 1980a,b, Rundlöf 2002, Mörseburg *et al.* 2005). The higher the tensile index of the fibre fraction, the lower is the increase in tensile index for a given addition of fines (Corson 1980, Rundlöf 2002).

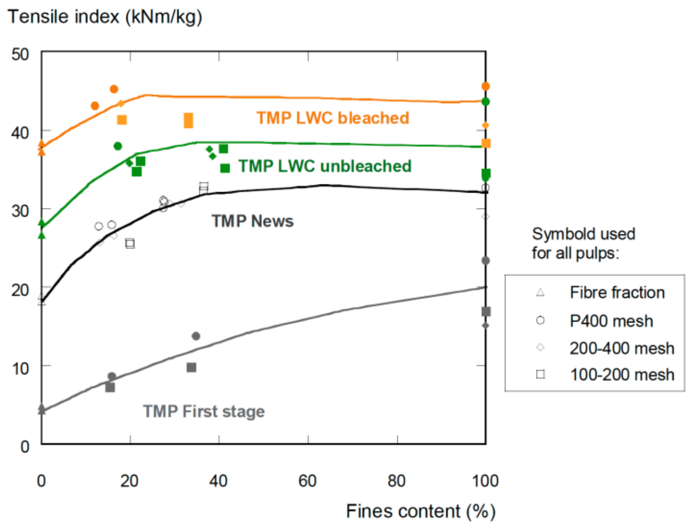

Figure 11. The increase in tensile index from addition of fines depends on the degree of fibre development (tensile index of the fibre fraction). Figure from Rundlöf (2002). The added fines were fractionated from respective pulp into different size classes using a BDDJ. Fractionation was repeated three times for each pulp using wires with successively larger apertures. Points with zero fines content are the fibre fractions remaining on the BDDJ 100 mesh wire to which fines were added.

3.4 Surface smoothness

Coarse mechanical pulp fibres have a negative impact on the surface smoothness and print quality of printing papers, especially for papers printed by the rotogravure process (Antoine *et al.* 1995). Fibres with low cell wall thickness (more earlywood like) and high flexibility (fibrillation) gives high surface smoothness (Hallamaa *et al.* 1999). In this work, the focus has been on newsprint and improved newsprint, which does not have a high demand on surface smoothness since these products are mostly printed by the offset, coldset or heatset processes. Surface smoothness is also difficult to evaluate on handsheets, due to the fact that all printing papers are calendered to some degree and this is difficult to simulate in lab-scale.

3.5 Other properties

Before the introduction of slotted wedge wire screen baskets, shives were a major cause of web breaks (Fjerdingen *et al.* 1997, Gregersen *et al.* 2000, Reme and Helle 2000). Therefore, **shive content** can be important to monitor for simplified process solutions.

Even though the elimination of open draws and installation of slotted screens have reduced the demand on fibre length (tear strength), there is likely a limit in **fibre length** below which the paper runnability is affected, even for modern production processes. However, the limit in fibre length seems to be lower for paper based on pulp produced in large DD refiners than for pulp produced in SD refiners, see section 8.6 and Sandberg *et al.* (2011).

Historically, pulp freeness (*e.g.*, Canadian Standard Freeness, CSF) which provides an indication of the dewatering rate of the pulp on a paper or board machine, has been the most utilized estimate of pulp quality. However, a given freeness can be achieved with different fibre property distributions and is therefore only a rough indicator of pulp quality (*e.g.*, Mörseburg *et al.* 2005).

Poorly developed fibres, *i.e.*, stiff fibres with a low degree of internal and external fibrillation are sometimes referred to as “coarse” fibres. Fibre analyzers often report a **fibre coarseness** value which is defined as the weight per unit length of fibre. This property has a clear limitation regarding the ability to describe the cross-sectional dimensions of fibres, which is illustrated in Figure 12. In this work, the notation “coarse fibres” is used as a broad term to denote poorly developed fibres, independent of cross-sectional dimensions.

Figure 12. Cross section of two schematic fibres that have the same coarseness, *i.e.*, the same weight per unit length, but very different paper making potential.

4 The mechanical pulping process

This chapter contains a brief description of the equipment used in refiner based mechanical pulping processes, the historical development and the most common process designs.

4.1 The refiner

4.1.1 History

The first refiner-like equipment that was used in wood based pulping processes, was the machine developed by Voith to make pulp out of SGW rejects in 1859 (Carpenter 1989). It was called a *raffineur* and it was initially equipped with sandstone discs. The first metal discs were used for refining of brown groundwood rejects in the end of the 19th century (Carpenter 1989). During the first half of the 20th century, refiner-based processes operating at high temperature (170-190°C) were developed for the production of hard-board from wood chips (Asplund 1934). During the 1950's the first attempts were made to utilize refiners for production of printing papers (Eberhardt 1955, 1956). Reading the paper presented by Asplund (1953), it is quite clear that he also experimented early with lower refining temperatures adapted for production of pulp for printing paper. The first refiners used for production of pulp for printing paper were non-pressurized open discharge refiners operating at relatively low consistency. The breakthrough for refiner produced pulp came when the thermomechanical pulping (TMP) process, with pressurized chip preheating and pressurized refining, was introduced (Asplund and Bystedt 1973, Charters and Ward 1973).

4.1.2 The high consistency refiner

As mentioned in section 2.3.5, it was not until the mid-1970's that the refiners could be operated at a consistency level above 30%, which today is referred to as high consistency (HC) refining. The increased consistency was made possible when the refiners were pressurized and thereby the steam flow was easier to handle (Ahrel and Bäck 1970, Charters and Ward 1973, Breck *et al.* 1975).

At an early stage, two major types of refiners were developed: double disc (DD) refiners, Figure 13A, equipped with two counter rotating discs by Bauer, later also by SCA/Sunds Defibrator (now Valmet), and single disc (SD) refiners, Figure 13B, by Defibrator, Jylhävaara, Sprout Waldron and Hymac (Carpenter 1989). Later, two additional design concepts were introduced to increase the capacity of a single refiner. The first was the Twin refiner, Figure

13C, essentially two SD refiners in one, developed by Sprout Waldron (now Andritz). The first mill installation involved a 45″ twin refiner in the Grand´Mère Mill in Canada, (Jones 1968). In a Twin refiner, the chips or pulp feed is split and fed to the two separate refining zones on each side of the rotor and the pulp and steam leaving the two zones are mixed in the refiner housing before exiting the refiner. The second concept was the conical disc (CD) refiner, Figure 13D, developed by Defibrator. The first installation was made in the Holmen Hallsta mill in Sweden, and involved a 70″ CD refiner (Tistad and Görfeldt 1981).

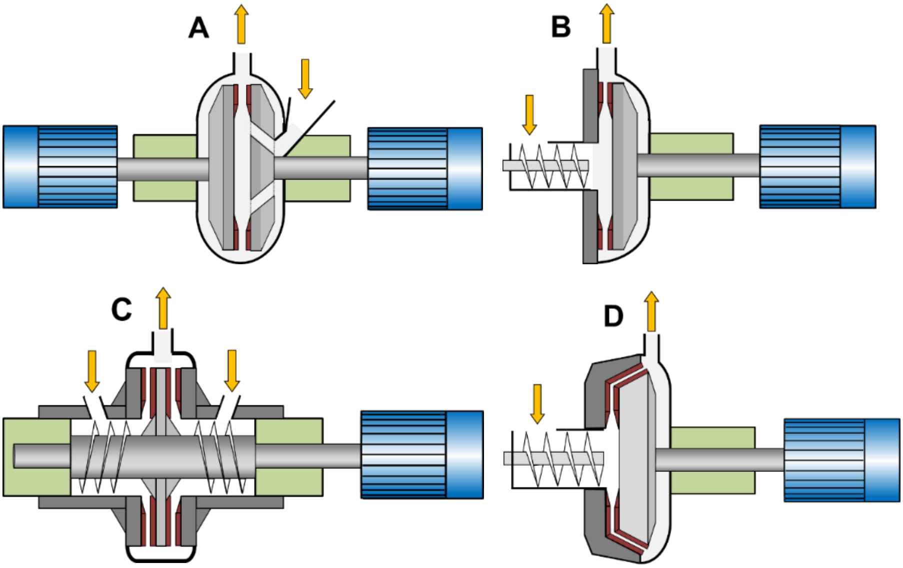

Figure 13. Schematic cross-sections of the most common HC refiner types: **A:** Double Disc, **B:** Single Disc, **C:** Twin and **D:** Conical Disc.

At a given production rate, the specific energy applied to the pulp is usually changed by adjustment of the disc gap and/or the dilution water flow rate, Figure 14. For most HC refiners, the disc gap is adjusted by means of a hydraulic system pressing the discs together. The dilution water is supplied to the chips and/or directly into the refining zone.

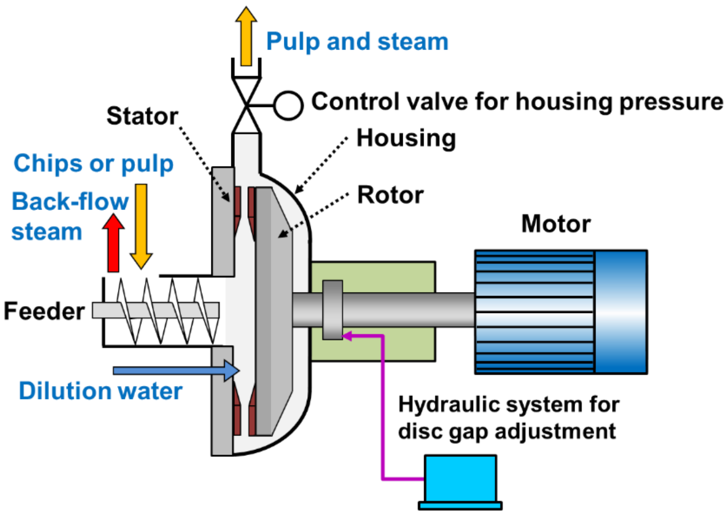

Figure 14. Schematic illustration of an SD HC refiner with main material flows (blue text) and main components (black text).

4.1.3 The low consistency refiner

Low consistency (LC) refiners have been utilized longer than HC refiners. The LC refiners of today have probably emerged from the development of Voith's Raffineur and the Jordan refiner that was developed for rag-pulp beating (Jordan and Eustice 1858). The first refiners with metal discs (not just metal bars as in Jordans) were introduced in the 1930's (Kloss 1937). They were gravity-fed and operated at consistencies in the range 3-15%. Refiners were not initially classified according to the feed consistency as they are today (low - LC, medium - MC and high - HC). Pump-fed refiners operating at 3-5% consistency with both pressurized feed and outlet, *i.e.*, machines called LC refiners today, were developed from the mid 1950's, Figure 15, (Jones and Cumpston 1954).

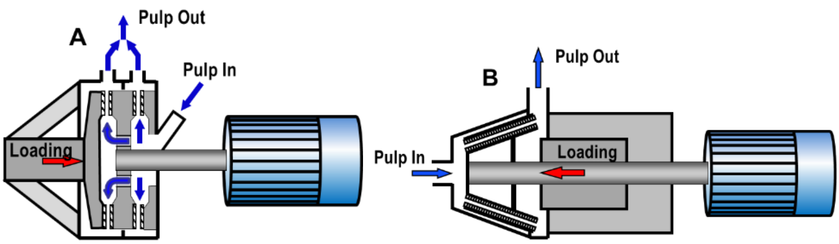

Figure 15. Schematic cross-sections of two of the LC refiner types used in this work: **A:** Flat disc (TwinFlo, Andritz) and **B:** Conical (RF, Valmet).

For mechanical pulp production, LC refining was used for rejects refining and post refining in SGW lines (Klemm 1957, de Montmorency 1962, Richardson 1969). It was however believed to be impossible to sufficiently develop fibre properties in LC refining (Kurdin 1974) and the incentive was mainly for shive reduction and for final freeness adjustment. However, some early studies showed that LC refining could also increase strength properties (Hoholik 1958, de Montmorency 1962). During the 1980's it was widely accepted that mechanical pulps require lower intensity during LC refining to avoid extensive fibre length reduction (Levlin 1980, Robinson *et al.* 1985), however, Kurdin (1974) had pointed this out earlier. There are also indications that it is beneficial to have high pulp temperature and pH to reduce fibre length loss in LC refining (Engstrand *et al.* 1990, Hammar *et al.* 2010).

At a given production rate, the specific energy applied in an LC refiner is normally changed by adjusting the disc gap. For most refiner types the gap adjustment is made with an electro-mechanical system.

4.2 Overview of the mechanical pulping process

In the following chapters, process configurations are illustrated with block diagrams. Symbols used are explained in Figure 16.

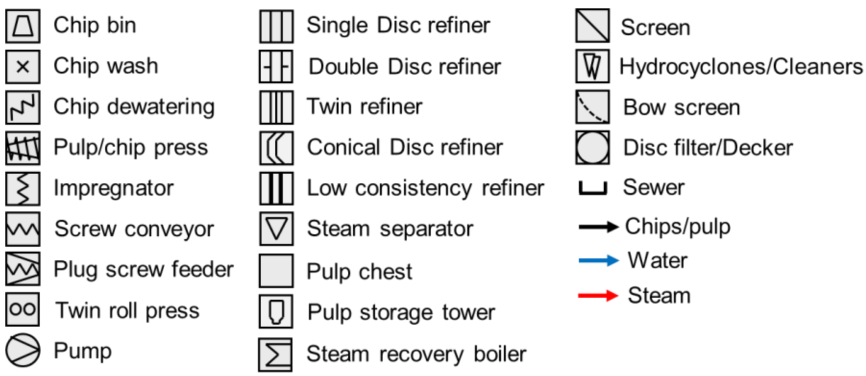

Figure 16. Symbols used in block diagrams.

Almost all refiner based mechanical pulping processes consist of four major process sections as shown in Figure 17: Chip pre-conditioning system, Main line refining, Fractionation (screening/cleaning) system and Rejects treatment system. These processes are described below. A more detailed description of the historical development of the mechanical pulping process is available in Sandberg *et al.* (2020).

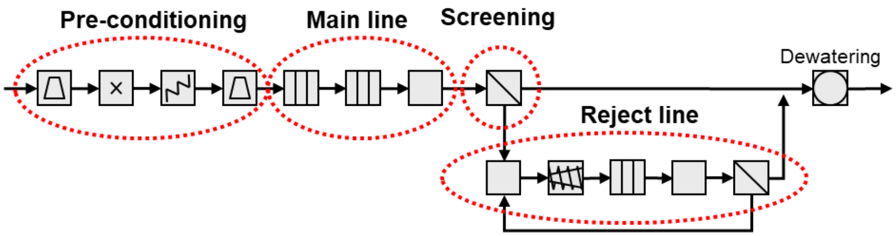

Figure 17. Overview of a TMP line showing the four main sections of the process (dashed circles).

There are considerable differences in process details between TMP lines over the world, however, a generalized process is described here:

Wood chips are presteamed, washed and preheated before being refined at a housing pressure of 3-4 bar(g). Refining is performed in one to three main line refining stages. After main line refining, the pulp is diluted with white water and agitated at 75 – 85°C at a consistency around 3%, for removal of latency (deflocculation and relaxation of stresses). The latency-treated pulp is screened for removal of shives (unseparated fibre bundles) and coarse fibres and finally the accepts fraction is usually dewatered in disc filters. The rejects are dewatered and refined at high consistency and thereafter the pulp is diluted and latency is removed before rejects screening. The rejects screen accepts are fed to the disc filters and the rejects are fed back to the main line rejects for additional refining.

Water from the disc filter and rejects dewatering is usually circulated as shown in Figure 18. It is important to have a water separation in the process between the pulp mill and the paper machine, especially if the pulp is bleached, in order to reduce carry-over of dissolved and colloidal substances (Käyhkö and Manner 2001).

Part of the steam produced in the refiners is used for preheating of chips and the rest is converted to clean steam in a reboiler and used for paper drying. In addition, heat is also usually transferred from the pulp mill white water to the paper machine by heat exchangers (not shown in Figure 18). Fresh water is supplied to the process at the paper machine and transported counter-current to the fibre flow. Some material, mainly dissolved and colloidal, is released from the pulp and removed from the process with the water to the effluent treatment plant. The yield of an unbleached refiner process (TMP) is therefore around 96% (Holmbom *et al.* 2005).

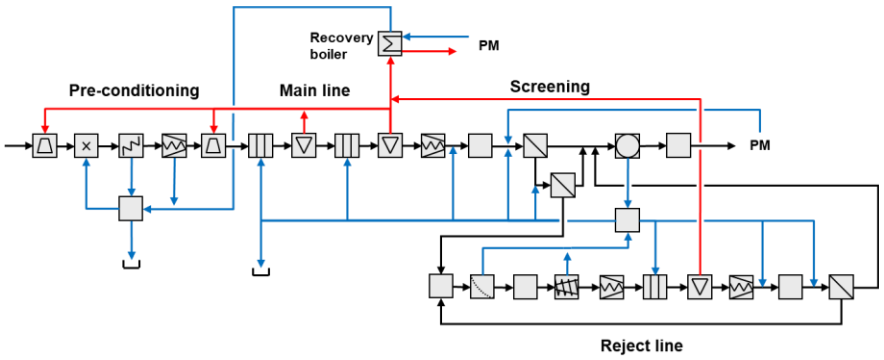

Figure 18. An example of a TMP process with principal equipment and main flows of fibre, water and steam. There are large variations in the main line refiner configuration.

4.3 Pre-conditioning

4.3.1 Preheating and washing

Most pre-conditioning systems begin with a presteaming bin in which chips are heated with steam produced in the refiners, Figure 19. The purpose of this step is to start the softening process and enhance the washing after the presteaming. In the chip washer, sand and other heavy debris is removed. Since the internal chip structure was to some extent filled by steam in the presteaming process, water will be drawn into the chips when they are soaked in the cooler water. After the chip washer, the chips are pumped to a dewatering screw and fed to a second bin. This bin can be pressurized and thus chips need to be fed into the bin either by a plug screw feeder or, less commonly, by a rotary valve.

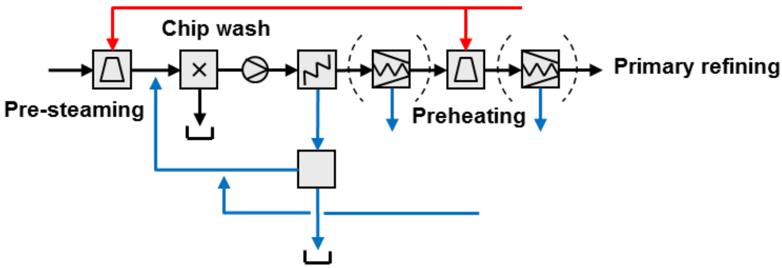

Figure 19. Pre-conditioning system in a refiner process. For a TMP process, the plug screw feeder is located before the preheater and for a PRMP after the preheater as indicated by the dashed parentheses.

Processes equipped with pressurized preheaters are referred to as thermomechanical pulping (TMP). In TMP processes there is often no plug screw feeder between the preheater and the refiner. This process was the most commonly installed process during the 1970's and 80's. Later, processes with atmospheric preheating were introduced in which the plug screw feeder is positioned between the preheater and refiner, Figure 19, (Sundholm and Mannström 1982, Jackson and Åkerlund 1984). Thereby the investment cost for the preheater was reduced. Some processes have a short preheating time (5-10 s) at high pressure (5-6 bar(g)) (Sabourin *et al.* 1997, Nelsson 2016). Pressurized refiners with atmospheric preheating should actually be referred to as PRMP (Pressurized Refiner Mechanical Pulp), but the acronym TMP is generally used for all pressurized refiner processes today.

4.3.2 Mechanical chip pretreatment

The pre-conditioning can include a chip compression and impregnation stage, Figure 20. Mechanical pretreatment has been utilized since the early days of RMP and is beneficial for handling of variations in the moisture content of the incoming wood chips and for reduction of extractives (Fournier *et al.* 1991, Tanase *et al.* 2010). The chip compression devices can be of the Impressafiner type (Andritz) or plug screw feeders (Valmet, Andritz). A comprehensive summary of mechanical chip pretreatment has been made by Gorski *et al.* (2010). A combination of chip pretreatment and high intensity refining is beneficial for fibre properties and energy efficiency (Kure *et al.* 1999b, Sabourin 2000, Nelsson *et al.* 2012).

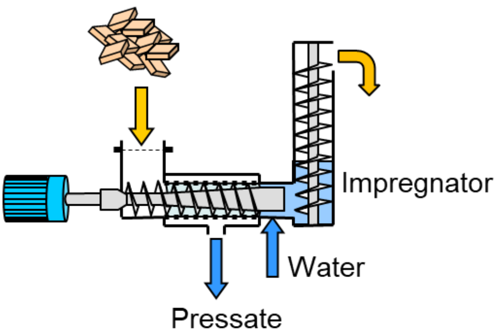

Figure 20. Example of a chip pretreatment system with water impregnation.

4.3.3 Chemical treatments in the process

Refining processes in which chemicals are introduced have been utilized since the mechanical pulp refiner was developed in the 1930's (Asplund 1953). Over the years, many different chemicals have been evaluated in different positions in the refining process, and it is not possible to provide a complete picture in this summary. However, some aspects are highlighted below.

Some of the positions where chemicals have been added include the following:

- To the chips (impregnation) before refining
- In the primary refiner directly into the refining zone or with the dilution water
- Between primary and secondary refiners (inter-stage treatment)
- After refining (post-treatment)
- To a specific fraction of the pulp *e.g.*, on screen rejects before refining

Beth *et al.* (1973) showed that charges of around 10 kg/ton of sodium sulphite to refining reduce the specific energy needed to a given burst strength by around 140 kWh/adt. The position of addition, type- and amount of chemicals will affect the resulting pulp properties and the yield at a given specific energy (*e.g.*, Costantino and Fisher 1983, Högman and Hartler 1988), see also section 2.2.4. A comprehensive overview of the early sulphite-based processes was made by Mackie and Taylor (1988). Later, processes utilizing alkaline peroxide, including chip pretreatment and/or refiner addition, were also developed (*e.g.*, Sandström *et al.* 1981, Xu 1999). The most common chemi-mechanical pulps today are sulphite- and/or sodium hydroxide-based chemi-thermomechanical pulp (CTMP) and alkaline peroxide mechanical pulp (APMP). Chemimechanical pulp has also been referred to as "ultra-high yield pulp" defined as a pulp having a yield above about 90% (*e.g.*, Atack *et al.* 1977).

At a given level of specific energy, most chemical treatments affect the pulp quality towards higher fibre length, higher tensile strength, lower light scattering and much lower shive content depending on how much and where in the process the chemicals are added (*e.g.*, Giertz 1968, Atack *et al.* 1977, Högman and Hartler 1988, Jones and Richardson 2001). Usually, chemical treatment of wood chips prior to refining reduces shive content and light scattering more than if chemicals are added later in the process.

There are studies showing that a combination of chemical treatments with high intensity refining (attained by increased rotational speed) can reduce the SRE required to reach a given tensile index or freeness, however most work published has been made in pilot scale (Stationwala 1994, Sabourin *et al.* 2003, Shagaev *et al.* 2005, Johansson *et al.* 2011) with a few exceptions which have been performed in mill scale (*e.g.*, Radhuber *et al.* 2016)

4.4 The main line

In the block diagrams below, some unit operations, such as plug screw feeders and steam separators, have been omitted to make the figures easier to read. Rejects dewatering is symbolized by a screw press only.

4.4.1 Historical development

The first refiner based mechanical pulping lines for printing paper consisted of two non-pressurised refining stages, Figure 21. The primary refining was done at higher consistency (first around 15%, later above 20%) and the secondary refining was performed at lower consistency (4-10%) (Eberhardt 1956). During the late 1960's it became more common to install processes with two stages of HC refining, often followed by a third LC refining stage. The process was initially referred to as *'refiner groundwood'* or *'super groundwood'* but later the term *'refiner mechanical pulp'* (RMP) was adopted. Today, the acronym RMP usually refers to non-pressurized refining.

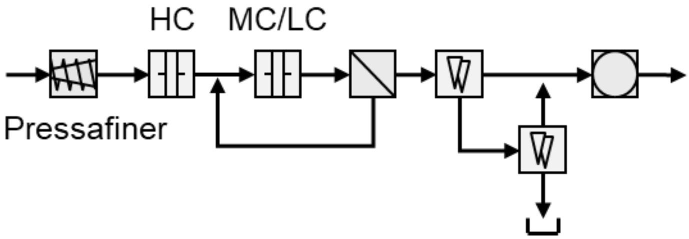

Figure 21. Early RMP process with mechanical chip pretreatment (Pressafiner) and second stage MC/LC refining. The screen rejects were fed back to the second stage refining; Redrawn from Eberhardt (1955).

When TMP was introduced, it was considered that the optimal refining temperature was between 120 and 130°C (Atack 1972, Asplund and Bystedt 1973, Higgins *et al.* 1978). In the beginning, only the first refining stage in the TMP lines was pressurized. The first two-stage pressurized TMP line was developed by Jylhävaara and the first mill installation was made at the Kaipola Mill in 1976 (Huusari and Syrjänen 1977). Later, it was realized that it was possible to raise the refining pressure (temperature) if the preheating temperature was reduced (Nunn and Thornton 1978, Huusari and Syrjänen 1981, Sundholm and Mannström 1982, Jackson and Åkerlund 1984). The increased refining pressure made it possible to recover steam from the refiners for paper drying without the need for steam compressors. The Kaipola mill in Finland was the first to install a reboiler for production of clean steam without steam compression in 1980 (Huusari and Syrjänen 1981).

4.4.2 Refiner configurations

At a given specific energy, the refiner type affects the pulp quality profile with decreasing fibre length and increasing light scattering in the order: CD, SD, DD (Jackson *et al.* 1986). RTS refiners produce pulp with properties in-between SD and DD (Holmen Paper experience, see chapter 8). Of course, the operating conditions for each refiner type have a large impact on the properties, but the general trend is as mentioned.

The process conditions during the initial fibre separation have a large impact on the attainable pulp properties. Therefore, the design of the main line refining is crucial (Atack 1972, Peterson and Dahlquist 1973, Falk *et al.* 1987, Heikkurinen *et al.* 1993, Stationwala *et al.*1993). As mentioned in section 2.3, the refining process can be divided in two different phases – defibration and fibrillation. Neill and Beath (1963) suggested that it ought to be beneficial to perform these two processes in separate machines. However, at the time, it was not known what refining conditions that were optimal for the two processes. Research during the 1980's showed that it was beneficial to perform the initial fibre separation at relatively low temperature and fibrillation at higher temperature (Salmén and Fellers 1982). Based on this concept, Valmet developed the "Thermopulp" process (Höglund *et al.* 1997) and later Andritz developed the ATMP process, Figure 22, in cooperation with Norske Skog (Sabourin *et al.* 2003, Hill *et al.* 2009). In contrast to this, it has been shown that high quality pulp can be produced with low specific energy in single-stage DD refining at high temperature (Muhic *et al.* 2010).

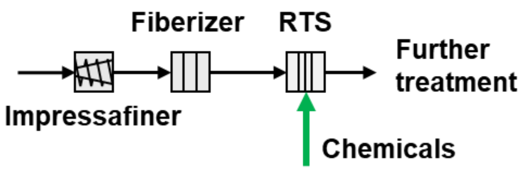

Figure 22. Schematic illustration of the ATMP (Advanced TMP) process. The fiberizer, in which defibration mainly takes place, is a "small" refiner operating at low specific energy, around 150 kWh/t, and at relatively low housing pressure (Sabourin *et al.* 2003, Hill *et al.* 2009).

4.4.3 Single-stage refining

The first RMP lines were usually installed with single-stage HC refining followed by a second LC refining stage. Later most of them were converted to multi-stage HC refining since the refiners usually were more stable and had longer segment life when operated at higher production rate in multi-stage configurations (Holzer *et al.* 1962, Gavelin 1966). On the other hand, Mills and Beath (1975) showed that it was possible to perform the main line refining in one stage at high consistency.

At the time, it was difficult to load DD refiners to the level required to reach the desired pulp freeness in a single-stage, especially for the larger DD refiners (Atack and Wood 1973). Mannström (1977) modified the feeding system to the Bauer DD refiners, which made it easier to run pressurized single-stage DD refiners to low freeness values (below 100 ml CSF). The first pressurized single-stage DD refiners were started up in the Summa mill, Finland, in 1977 (Skinnar 1979). Braviken installed a single-stage PRMP SD refiner in 1983 (Jackson and Åkerlund 1983).

It has been pointed out that single-stage processes are easier to control and maintain (Mills and Beath 1975). With DD refiners, single-stage operations also have higher energy efficiency (Peterson and Dahlqvist 1973). On the other hand, Wild and Steeves (1972) and Mihelich *et al.* (1972) reported that there was no significant difference in energy efficiency and pulp quality for single versus two-stage refining with the same refiner type.

In later applications of single-stage refining for printing paper, high intensity chip refining such as DD or RTS have mainly been utilized. A single-stage design with a modern slotted screening system is shown in Figure 23. Examples of such systems are Perlen (RTS) (Aregger 2001) and Kvarnsveden (DD) (Ferritsius 2020). Single-stage HC refining is also common in new hardwood BCTMP lines (Guangdong *et al.* 2011, Peng *et al.* 2018).

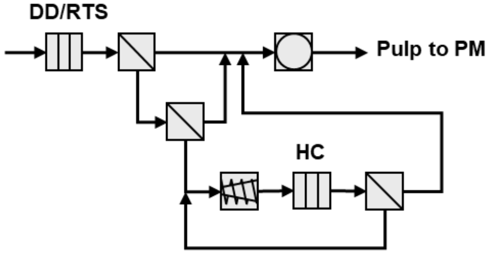

Figure 23. Example of a TMP process with single-stage main line refining.

4.4.4 Low consistency refining

In the early days of RMP, LC refining was used for second or third stage refining in the main line, often combined with screen rejects, Figure 21, (Eberhardt 1955). A similar process, without Pressafiner and cleaners, was also in operation at the Boyer Mill, Tasmania, with DD primary refiners (Bonham *et al.* 1983) and this concept was tested in the Kvarnsveden mill in Sweden (Strand *et al.* 1993). During the most expansive period of the TMP development, there were few LC refiners installed in TMP lines. However, from the mid-1990's the number of LC refiners employed in TMP lines increased, mainly installed for third stage main line refining (Musselman *et al.* 1997, Cannell 2002). At the time, the incentives for such installations were a cost effective 10-15% increase of production capacity and a reduced specific energy to a given pulp quality. de Montmorency (1958) showed similar results for LC refining of SGW produced at increased production rate.

Several studies have shown that it is beneficial for loadability (applied power at a given production rate) and fibre length preservation to apply LC refining to a pulp stream enriched in long fibres (Kilpper and Baumgartner 1977, Sandberg *et al.* 2009, Andersson *et al.* 2012b, Miller *et al.* 2017). Shagaev and Bergström (2005) and Sandberg and Shagaev (2011) have shown that a fibre fraction enriched in transition wood fibres obtained as an intermediate hydrocyclone fraction can withstand a high load in LC refining. A process with two-stage HC refining followed by LC refining and screening, where the screen rejects are fed back to the LC refiners, is in operation in the Skogn mill in Norway (Imppola *et al.* 2013).

The specific energy required in LC refining for a given tensile index increase or freeness reduction is approximately half of that required for HC refining (Berger 1995, Sandberg *et al.* 2009, Gorski *et al.* 2012). Fibres are, however, developed differently in LC refining than in HC refining. Fibres are straightened in LC refining and fibre walls are not peeled and externally fibrillated to the same extent as in HC refiners, which results in pulps with lower light scattering at a given tensile index compared to HC refining (Sandberg *et al.* 2009, Ferritsius *et al.* 2012). Since light scattering is not significantly increased over LC refining, it is preferable to combine it with high intensity HC refining (Andersson *et al.* 2012a).

4.5 Latency treatment

After HC refining, fibres are twisted and curled as well as entangled in flocs. When the pulp leaves the high temperature environment, the deformations are frozen into the fibre structure and this condition is referred to as "latency" (Beath *et al.* 1966). Usually, latency is removed in agitated chests at approximately 3% consistency and 70-90°C for 20-60 minutes. Recent research has shown that free fibres are straightened in seconds in hot water and that the deflocculation is the rate-controlling mechanism in latency removal (Gao 2014). The deflocculation rate depends strongly on the applied energy intensity. Thus, latency can be removed more efficiently in a smaller volume with lower energy consumption by intense mechanical treatment at high temperature under a short time. This was also proposed earlier by Karnis (1979), but the mechanisms were not established at the time. Moreover, Sund *et al.* (2021) showed that it is preferable for good refiner control to have a rather small and well mixed chest (around 5 minutes residence time) after refining. Beath *et al.* (1966) and Welch (1999) showed that conventional latency treatment can be replaced with an LC refining stage operating at a sufficiently high temperature.

4.6 Fractionation – Screening/Cleaning

Fractionation is a term that has been used in different ways in the pulp and paper industry. The definition of fractionation is that a pulp is divided into two (or more) streams, each stream having different properties. The difference can be associated with any fibre-related property such as fibre length, fibre wall thickness, degree of external fibrillation, proportion of fines, etc.) When the word fractionation is used, it is important to specify to what pulp property the fractionation is intended. The most common fractionation is according to fibre length and often this is not specified in the literature. The main purpose of fractionation equipment is to remove particles from the pulp that have a negative effect on the properties of the final product. The most common disturbing particles affecting print quality and runnability are shives and coarse fibres (Sears *et al.* 1964, Kartovaara 1990, Zou 2007).

Cleaning is a special case of fractionation, in which a small fraction of debris, which cannot be upgraded to usable material (*e.g.*, bark, sand, etc.), is removed from the process. Below, the term *fractionation* will be used for processes where a larger part of the pulp is separated for rejects refining and *cleaning* for a process where the rejects are sewered. The term *screen room* is used for the whole fractionation and cleaning systems.

Two major equipment categories, screens and hydrocyclones, are utilized for fractionation. Hydrocyclones are often referred to as cleaners, which is misleading, since hydrocyclones can also be used for fibre fractionation. Thus, both screens and hydrocyclones can be used for cleaning and for fractionation. However, in mechanical pulping processes, screens are seldom used for cleaning, as they are in recycled fibre processes and in paper- and board machine stock preparation systems.

Screens separate particles mainly according to size, *e.g.*, fibre length and shive size (Hill *et al.* 1975, Karnis 1997, Wakelin *et al.* 1999). Modern narrow slotted screens are often referred to as barrier screens, since the separation of larger shives is almost 100%.

Hydrocyclones, on the other hand, fractionate according to specific surface and density (Wood and Karnis 1979, Karnis 1982, Sandberg *et al.* 1997, Wakelin *et al.* 1999, Ouellet *et al.* 2003). Thus, at moderate rejects rates, fibre length is normally not affected by hydrocyclone fractionation. Hydrocyclones have higher separation efficiency for thick-walled latewood fibres and poorly fibrillated fibres compared to screens. Both screens and hydrocyclones are normally arranged in two or more stages to improve the selectivity of the separation (Friesen *et al.* 2003).

In the early days of RMP, the fractionation systems were similar to those used for SGW and consisted of combinations of open screens and cleaners in different combinations (Eberhardt 1955, Gavelin 1966). Cleaners were necessary to achieve sufficient reduction of the rather large amount of chops (small cubical shives) produced in the non-pressurized refiners.

Initially, when the TMP process was introduced, the screen rooms were similar to those used for RMP, as exemplified in Figure 24.

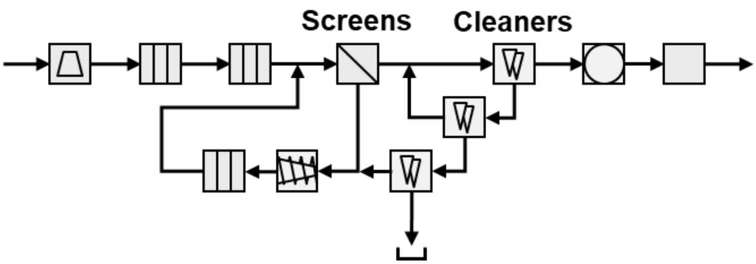

Figure 24. Example of an early screen room configuration for TMP, redrawn from Asplund and Bystedt (1973).

When TMP was introduced, shive content was reduced so much that it was discussed whether screening was necessary at all (Kurdin 1979). A few mills were actually operating without screens in the pulp mill, at least for a period of time (Butcher 1975, Skinnar 1979). Gustavsson and Vihmari (1977) also suggested that the rejects system in a TMP line could be replaced with a LC post-refining stage. This idea was however not pursued further, most likely due to increased demand on paper quality.

A large improvement in the screening process occurred when wedge wire slotted screen baskets were introduced during the 1990's. The large increase in shive removal efficiency achieved by slotted screen baskets rendered the cleaner systems superfluous, at least for newsprint, and they were removed in many mills (Cannell 1999). The system design of the screening operation also changed from feeding the second stage accepts backwards to feeding it forward, leading to the most common screen configuration of today, Figure 23. When TMP was introduced, it was also suggested that more energy should be applied in the main line and thereby the screens could be omitted and only cleaners used in the screen rooms (Ahrel 1973, Hofmann 1975).

Much research has been made on concepts where the pulp from primary stage refining is fractionated into a coarser fraction sent to further refining and a finer fraction that is fed directly to dewatering. Such process concepts were utilized already in some SGW processes (Hoholik 1959). The refining process results in a strongly heterogenic material, and the thought has been that it ought to be more energy efficient to do limited initial refining and separate the poorly developed fibres for additional refining (Gavelin 1966, St. Laurent *et al.* 1993, Nurminen and Liukkonen 2001, Ferluc *et al.* 2008). One major problem with this idea is how to achieve the fibre fractionation with high efficiency. Screens have a low ability to separate fibres according to the degree of fibre development (fibrillation, bonding). Hydrocyclones have, as mentioned above, higher separation efficiency than screens in this respect, but they suffer from the large disadvantage that a feed consistency preferably below 0.7% is needed to achieve high fractionation efficiency and thereby a much larger dewatering capacity is required. Moreover, there are studies that indicate that also the bonding properties of the primary fines are developed upon refining, see section 2.3.4. Therefore, it might not be beneficial to bypass the "finer" fractions and only refine the coarser fibres.

4.7 Rejects refining

In the early RMP processes, rejects refining was performed at low consistency either together with the primary stage pulp, Figure 21, or in a dedicated refiner similar to the configuration shown in Figure 24.

The concept with combined rejects and second stage main line refining was also applied in RMP systems with HC refining (Sprout Waldron) already in the 1960's (Jones 1968, Ulander 1985). The main line consisted of two or three HC refiners in series with the thickened screen rejects mixed with primary stage pulp before the second refining stage, Figure 25. The pulp quality was rather difficult to control with this concept, and the process is no longer in widespread use.

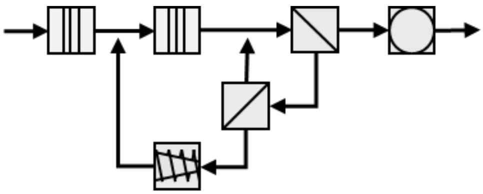

Figure 25. TMP system with screen rejects fed back to second stage main line refining, redrawn from Ulander (1985).

For printing paper, the most common rejects treatment is single-stage HC refining. Other variations include two-stage HC refining and HC-LC refining (Hooper 1990, Viljakainen *et al.* 1997, Sandberg *et al.* 2009, Amiri *et al.* 2016).

In the RMP lines it was common with LC refining of rejects, as mentioned above. A process configuration with extended main line refining and only LC rejects refining was in operation for a period at the Port Hawkesbury mill (Moqvist *et al.* 2005). Nowadays, this approach is rare and for printing paper, the TMP line in the Skogn mill, Norway, is, to my knowledge, the only one in operation where rejects are refined in LC refiners only, (Imppola *et al.* 2013). However, in the Skogn mill, LC refining is carried out on mixed main line pulp and rejects.

With LC rejects refining, the process is simplified since the entire HC rejects refining process is omitted.

5 Knowledge gap

Based on the literature review in the introduction (chapters 2 to 4), the following conclusions are made and questions raised:

Single-stage HC refining was utilized early in the refiner-based production processes. It was debated whether this approach was more advantageous or not, compared to two-stage refining. However, over the years, two-stage processes have dominated. Even when larger DD refiners were introduced, two-stage processes were first recommended. A clear advantage of single-stage HC refining for simplified processes is that it is easier to control.

1. *What refining conditions are needed to enable a level of fibre development in a single-stage refiner such that no or only a little more development is needed to attain final pulp quality?*

Low consistency refining has been shown to reduce the specific energy demand to a given freeness or tensile index, but it has also been shown that pulp properties are not developed in the same way as in HC refining.

2. *How and to what degree can LC refining be used in a simplified TMP process?*

Fractionation of the pulp and further treatment of the long-fibre fraction has been considered necessary to attain appropriate pulp quality. In addition to separation of long-fibres, screens and hydrocyclones remove shives which can affect runnability and print quality.

3. *How should a process be designed to make it possible to omit screening and rejects treatment*?

Decreased process complexity has not been a main focus in published work on TMP process development, even though it has been mentioned in a few cases.

At the 1977 International Mechanical Pulping Conference, Atack (1977) stated in his concluding remarks that "Disappointingly, there has been little attempt described this week to simplify flow lines. In fact, it would appear that in many cases systems have tended to become increasingly and, in my view, unnecessarily more complex."

Summing up:

How should a process for mechanical pulp production be designed and operated to attain sufficiently developed fibres and fines with a reduced number of unit operations and increased energy efficiency?

6 Methods

In this chapter a summary of data acquisition, calculations and pulp analyses are presented. Since one of the goals of this work is to reduce the specific energy demand, a section is dedicated to a discussion of energy efficiency. Detailed presentations of the methods and pulp and paper characterisation used are found in Papers I-VII.

6.1 Process data

Motor power, flow rates, etc. were logged from the mill DCS and average values during the sampling time (usually 5-15 minutes depending on sampling position) are presented in tables and figures.

In all trials, production rates were calculated from pulp flow rate from the chest after the refiner(s) and lab-calibrated consistency measured in the same position. Production rate is presented as air-dry metric tons per hour (adt/h).

The specific energy is presented in kilowatt hours per air-dry ton (kWh/adt) if not otherwise stated. The specific refining energy reported include all losses such as motor losses and refiner no-load power.

Most comparisons are made at a tensile index level corresponding to newsprint final pulp (around 50 Nm/g measured on Rapid-Köthen handsheets or 42 Nm/g measured on ISO handsheets)

6.2 Energy Efficiency

Increased energy efficiency, *i.e.*, reduced specific electrical energy demand, is one of the goals of this work. However, it is not a simple matter to define efficiency for mechanical pulping (Sandberg *et al.* 2021). Campbell (1934) made reference to this issue already in the early 1930's and still today there is no generally accepted definition that can be used for all mechanical pulping processes. Campbell (1934) and later also Atack (1981) pointed out that the specific energy or efficiency ought to be related to pulp quality. That is a complex matter, since mechanical pulp is such a heterogenous material and commonly used pulp quality measures, such as tensile index or freeness, can be attained with different fibre property distributions (Ferritsius *et al.* 2020, Ferritsius 2021).

Sandberg *et al.* (2021) suggested that the efficiency for a machine or process section can be expressed as:

$$Efficiency, \eta = \frac{\Delta p}{E_S} \tag{1}$$

where Δp is the change in a fibre or pulp property over the process stage and E_S is the supplied specific energy. Similar definitions have been used earlier (Brecht and Müller 1952, Johansson *et al.* 2007, Ferritsius *et al.* 2014) but it has a major limitation in that it is difficult to use for processes where the feed material is wood chips.

However, Sandberg *et al.* (2021) pointed out that, if two processes or two operating conditions are compared and pulp or fibre properties are available at the same level and the feed material is the same, a relative difference in efficiency can be calculated:

$$Relative\ difference\ in\ efficiency\ = \frac{SRE_1}{SRE_2} - 1 \quad (2)$$

It should be kept in mind that it is probably impossible to fully describe the pulp quality with a single number and therefore an efficiency calculated from Equation 1 has limitations.

In this work I have, in most cases, chosen to relate the specific refining energy (SRE) to tensile index when efficiency is discussed. For some studies, an efficiency based on Equation 1 with tensile index increase (ΔTI) as the change in pulp property has been used, *i.e.*, $\eta = \Delta TI/SRE$.

6.3 Pulp and paper analyses

6.3.1 Choice of pulp analyses

Characterization of mechanical pulps is not straight forward. Often a large number of measured properties are presented in R&D work intended to give a picture of different aspects of the behaviour of the pulp. As discussed in chapter 3, there are several properties that are important for printing papers. Moreover, many of the measured properties covary, *i.e.*, they are not independent properties (Ferritsius 2021). One approach has been to describe the pulp with independent factors based on multivariate data analyses (*e.g.*, Strand 1987, Ferritsius 2021). This approach has not been used in the present work.

The experiences from paper production in Braviken is that tensile strength and strain at break are two important properties of the paper affecting the runnability both on the PM and in the printing press. Fibre length has an effect also, but other fibre properties can reduce the importance of the length (Sandberg *et al.* 2011).

Based on these experiences I have chosen to relate the specific energy to tensile index measured on handsheets, as an indication of the "bonding potential", when efficiency is discussed. In one study, Paper VI, sheet density and Z-strength were measured on fibre fraction handsheets to evaluate the bonding ability of fibres (Jackson and Williams 1979, Andersson and Mohlin 1980).

In previous work, we have experienced that it can be difficult to maintain light scattering when the process is developed towards lower specific refining energy (Andersson *et al.* 2012a, Nelsson *et al.* 2015). The light scattering coefficient is the optical property that is mostly affected in the investigated processes, therefore, it is the only optical property that is presented in all investigations.

Shives might represent a potential problem when the process is simplified and therefore the shive content is presented for all investigations. In the studies reported in papers V and VI, more detailed fibre analyses (fibre wall thickness, fibre curl, internal and external fibrillation) were performed in order to obtain a deeper understanding of how fibres and fines are developed in the processes.

In two mill trials, simplified processes were evaluated on the paper machines in Braviken, Papers III and IV, and for those trials, properties of the produced paper are presented. Surface smoothness has not been evaluated in the present work except for the paper machine trials.

6.3.2 Pulp analyses

Detailed descriptions of pulp analyses are provided in Papers I-VII. All pulps included in this work were analysed in the Braviken mill laboratory. Pulp samples from each operation point were divided into two, or sometimes three, sub-samples before analyses. Each subsample was measured twice in an optical pulp analyser, PulpEye (PulpEye, Örnsköldsvik, Sweden). Thus, the presented handsheet properties are averages of 2-3 measurements and shive contents and fibre lengths are averages of 4-6 measurements.

In the investigations presented in Papers V and VI, pulp samples were also analyzed in the laboratories at the Kvarnsveden mill, Valmet – Sundsvall, RISE PFI – Trondheim and SLU - Uppsala.

All samples were hot disintegrated according to ISO 5263-3:2004 before analysis.

In all trials, **handsheet properties** were measured on Rapid-Köthen handsheets (denoted R-K, ISO 5269-2). In Papers V and VI properties were also measured on handsheets prepared according to ISO 5270:2012 (denoted ISO to distinguish from R-K). At a R-K tensile index around 50 Nm/g, the values are around 8 Nm/g higher than ISO values, which in this case would be around 42 Nm/g. All handsheets were prepared without white water recirculation.

Handsheets (R-K and ISO) were also prepared from fibre fractions obtained from Bauer McNett fractionators, BMcN >50, (SCAN-CM 6:05:2005).

Fibre properties: Fibre length was measured with a PulpEye optical fibre analyzer and presented as the length-weighted average because this was the standard used in the Braviken mill at the time of the evaluations. It has, however, been shown recently that length-length-weighted average fibre length provides a better representation of the amount of long-fibre in a pulp (Ferritsius 2021). Therefore, in Papers V and VI, length-length-weighted average fibre length is presented, measured with another optical fibre analyzer, FiberLab (Valmet, Espoo, Finland). Arithmetic length-width distributions of fines, presented in Paper VI, were measured with an FS5 fibre analyzer (Valmet, Espoo, Finland).

Fibre curl and external fibrillation were measured with FibreLab and internal fibrillation was measured by SLU according to a modified Simons' stain method described by Fernando and Daniel (2010). Fibre wall thickness was measured at RISE PFI according to a method described by Reme *et al.* (2002).

Shive content was analysed with a PulpEye (same as above) for which shives were defined as particles wider than 75 µm and longer than 300 µm. In two studies, the shive content was also measured with a Somerville screen, 150 µm slots, according to (Tappi T275 sp-18).

6.3.3 Paper analyses

Testing of paper produced on the paper machines in Braviken was performed with an L&W Autoline (Lorentzen & Wettre – ABB, Kista, Sweden).

7 Mill trials

The described mill scale trials have been made over a period of several years. Over time, several process configurations have been investigated, mainly in the Holmen Braviken mill, but also in the Holmen Hallsta mill as well as in the Stora Enso Kvarnsveden mill. The raw material for all trials was Norway spruce (Picea abies), however with different proportions of roundwood and sawmill chips (0-30% sawmill chips).

In this chapter, the investigated process configurations are presented briefly in process order rather than in chronological order. All trials and investigations described in papers I – VII are not presented in the thesis since some of them do not contribute to the two major objectives of the thesis which were to simplify the process and increase the energy efficiency for mechanical pulping. Detailed trial descriptions and process conditions are found in Papers I-VII.

7.1 Process nomenclature

For ease of reading texts and graphs in the following chapters, the evaluated process configurations are denoted with abbreviations. The processes are described based on main line and rejects refiner types, process conditions and configurations. The following terminology is used:

CD	Conical disc HC refining
CPT:S	Compressive chip pretreatment with an Impressafiner followed by impregnation with sulphite
CPT:W	Compressive chip pretreatment with an Impressafiner followed by impregnation with water.
DD	Double disc HC refining
DDc	Double disc HC refining with coarse bidirectional segments
DDf	Double disc HC refining with fine bidirectional segments
DDu	Double disc HC refining with unidirectional (feeding) segments
F	Fractionation with screens (used in combination with LC refining, LC-F)
HT	Operation of DD refiners at increased housing pressure, HT:DD
LC	Low consistency refining
RTS	Single disc HC refining at high rotational speed (2300 rpm) and higher refiner pressure (5.5 bar(g))
S	Sulphite added to chips or pulp right before a refiner, S:DD, RTS-S:SD
SD	Single disc HC refining, (A special type of SD refiner, the Twin refiner, has also been used in reference processes. All refiner types are presented in section 4.1.)

In processes involving several stages, a hyphen (-) between two abbreviations indicates that the machines are arranged in series and when a plus sign (+) is included, the notation after the plus sign refers to the rejects line configuration. For example, the process in Figure 17, which consists of two-stage single disc HC refining in the main-line and single-stage single disc HC refining in the rejects line, is denoted SD-SD+SD.

In one study, combinations of HC refining, LC refining and screen fractionation were evaluated. These processes are abbreviated with the primary HC refiner type (SD/DD), LC and F for fractionation with screens, for example DD-LC-F, Figure33. This study is presented in detail in Paper III, and therein the abbreviation S is used for screen fractionation, but in this thesis, S is used to denote addition of sulphite.

Since DD refiners in both Braviken and Kvarnsveden have been studied, the DD notation is followed by a *K* for *Kvarnsveden*. Over time, the production rates for the DD refiners in both mills have been increased and this has had a large effect on the energy efficiency. To distinguish the differences in production rate, a number representing the production rate in adt/h is included in the legend for some figures.

As an example, "DDf K 11 t/h" refers to a DD refiner in Kvarnsveden equipped with fine bidirectional segments operating at 11 adt/h.

The investigated production lines are both TMP and PRMP lines, *i.e.*, some have pressurized and others have atmospheric preheating. For simplicity, all lines will be denoted as TMP lines in the following text, for details, see Papers I-VII.

7.2 Reference processes – a continuous development

Around the year 2000, all three TMP lines in the Braviken mill had similar configurations, based on two-stage SD HC main line refining, Figure 26. After latency treatment, the pulp was fractionated in screens (0.15 mm slots) and hydrocyclones. The rejects from both systems were mixed, dewatered and refined in SD HC refiners. The refined rejects were handled somewhat differently in the TMP lines but in all lines, they were fractionated with both screens and hydrocyclones.

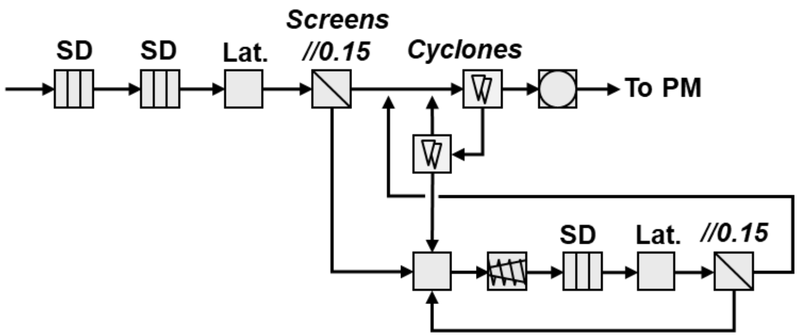

Figure 26. Generalized process configuration of the TMP lines, based on two-stage SD HC main line refining, in the Braviken and Hallsta mills around the year 2000. Hallsta did not, and still does not, have fractionating hydrocyclones.

The main line refiner configurations differed somewhat between the lines in Braviken: two TMP lines had 4 parallel RLP58 primary refiners followed by 3 parallel RL58 second stage refiners. The third line has two Twin 60 refiners in series and, in parallel, a CD70 and an RGP262 in series, Figure 27. The rejects refining differed also between the TMP lines, one had two-stage HC rejects refining and the other two had single-stage HC rejects refining.

At the time, the Hallsta mill had a similar process configuration as that shown in Figure 26, however without fractionating hydrocyclones. In 2002, two of the four main lines in TMP3 in Hallsta were modified to RTS in the primary stage, Figure 29.

Over time, all TMP lines in the mills have been improved in terms of energy demand and pulp quality and therefore, some of the trial configurations evaluated in papers II and III, are used in the reference process in Paper VI. Thus, different reference processes have been used in the investigations, depending on the purpose of the trial and what was considered "state of the art" in the mill at the time of the respective trial. During the first decade of the 21st century, LC refining was installed in one of the RLP58-lines and in the Twin60 line in Braviken, Figure 27, as well as in the RTS line in Hallsta, Figure 29. As a base line reference, data from the RLP58 main line and final pulp is included for comparison in most of the graphs in chapter 8. The configuration of the TMP mill in Braviken today (2022) is shown in Appendix 1.

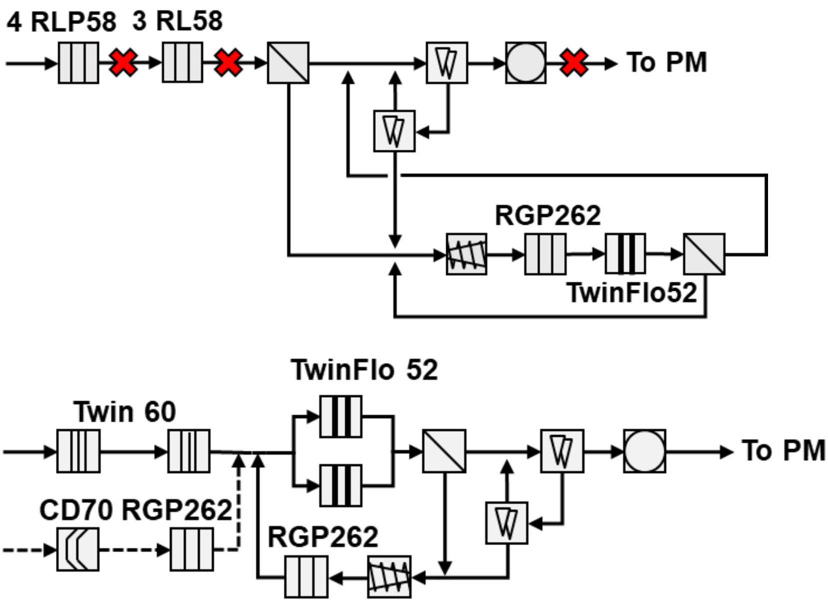

Figure 27. Configurations for two newsprint TMP lines in Braviken. **Top**: The RLP58 line (configuration between 2003 and 2008) is used as base reference in most graphs in chapter 8. Sample points are shown with red crosses. The RLP58 line is no longer in operation with this configuration. **Bottom**: The Twin60 line (configuration between 2005 and 2017).

7.3 Approaches

A large number of process concepts have been evaluated in which different approaches have been used to reduce the specific refining energy:

1. Impressafiner chip pretreatment
2. Addition of low charges of sulphite
3. Primary refiner type
4. Single-stage HC main line refining
5. Segment and centre plate design
6. Increased production rate
7. Increased refining temperature (housing pressure)
8. LC refining in different positions and combined with different HC refiner types

The separate effects of all these techniques have not been evaluated systematically neither have potential synergistic effects of all possible combinations been investigated.

The choice of operating conditions during trials was based on some of the earlier published work (Muhic 2010, Andersson 2011, Nelsson 2016) and pre-trials that are not reported here.

In Figure 28, a schematic overview of the studied process configurations is shown. The figure is schematic and does not show all studied processes but includes the main approaches listed above.

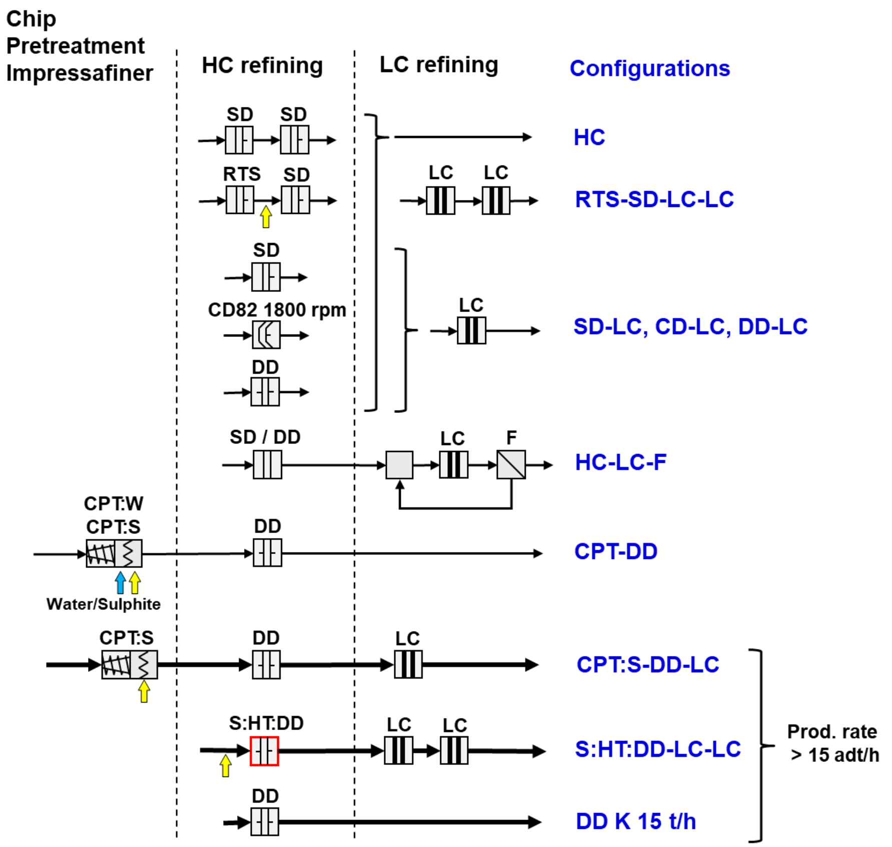

Figure 28. Overview of the studied process configurations. The figure is schematic and does not show all 17 processes that are presented in chapter 8. Yellow arrows represent sulphite addition and the blue arrow water.

7.5 Main line configurations

Several main-line configurations have been investigated in this work:

1.	SD-SD	Two-stage SD HC refining
2.	SD-LC	Single-stage SD HC refining followed by LC refining
3.	CD	Single-stage CD HC refining, 1800 rpm
4.	CD-LC	Single-stage CD HC refining, 1800 rpm, followed by LC refining
5.	DD	Single-stage DD HC refining
6.	DD-LC	Single-stage DD HC refining followed by LC refining
7.	CPT:W/S-DD	Chip pretreatment with water or sulphite before single-stage DD refining
8.	CPT:S-DD-LC	Chip pretreatment with sulphite before DD refining followed by LC refining
9.	S:HT:DD-LC-LC	Sulphite added right before a DD refiner operating at high housing pressure followed by two-stage LC refining
10.	RTS-SD	RTS primary refining, 2300 rpm, followed by SD HC refining
11.	RTS-SD-LC-LC	followed by two-stage LC refining
12.	RTS-S:SD	Same HC refiners as № 10 with sulphite addition before the second stage refining

All HC refiners used in the list above operate at 1500 rpm except the CD in Kvarnsveden (№ 3 and 4) and the RTS in Hallsta (№ 10-12). Refiner types and process conditions are presented briefly below, for details, see Papers I-VII.

7.5.1 HC refining

It is well known that the primary stage refining conditions are important for the further development of the fibres, and they define the property range that can be attained upon further refining, section 2.3.1. Therefore, four types of primary HC refiners (SD, CD, DD and RTS) have been studied alone and in combination with LC refining in this work, Papers I-VII. Since one goal of this work is to simplify the production process, it is important to have well developed fibres and a low shive content from the main line.

Single Disc (SD) refining (Paper II, III, IV, VI)

Three types of SD HC main line refiners were used in the process evaluations and reference processes: RLP58/RL58 (Defibrator), SD65 (Jylhä) and Twin 60 (Andritz). The pressurized primary RLP58 refiners were used together with atmospheric second stage RL58 refiners and later as single-stage HC refiners before LC refining (see below). The Jylhä SD65 refiners were operating as second stage units in the RTS lines in Hallsta and the Twin 60 refiners were utilized in reference processes.

Conical Disc (CD) refining (Paper V)

Samples were also taken from a single-stage RGP82CD HC refiner, referred to below as CD82, operating at 13 adt/h production rate in the Stora Enso Kvarnsveden mill, Borlänge, Sweden. The CD82 refiner was equipped with a gearbox and was operating at 1800 rpm. After the CD82 refiner, the pulp was refined in a second stage CF82 LC refiner (section 7.4.3).

Double Disc (DD) refining (Papers I-VII)

In 2008, a new TMP line was started-up in Braviken mainly used for directory paper production. The TMP line incorporated chip pretreatment with an Impressafiner, three parallel RGP68DD single-stage HC double disc refiners and a new type of TwinFlo LC refiner with a 72″ diameter. The DD refiners have been studied together with chip pretreatment and LC refining. Trials with the DD refiners in Braviken are described further below.

Single-stage DD HC refining (RGP68DD) operating at 11 adt/h production rate with and without proceeding LC refining was also studied in the Kvarnsveden mill, Paper V. Later, a study was also made at 15.5 adt/h production rate and normal housing pressure, 4 bar, and with no sodium sulphite added. The same type of segment design (DN72N 828I/847K, Valmet) was used in this study as in the S:HT:DDc-LC-LC trial in Braviken, section 7.4.4. The raw material was Norway spruce roundwood. Results from this trial have not been published, but are included in this thesis since they are interesting for the work with simplified processes.

RTS refining (Paper V)

The main line of TMP3 in the Holmen Hallsta mill is shown in Figure 29. The RTS refiners are SB170 units (Andritz) operating at 2300 rpm and 5.5 bar housing pressure. Each RTS refiner supplies pulp to one second stage Jylhä SD65 HC refiner (Valmet). In this study, only the two RTS-lines were in operation followed by the LC refining stage. The data are used for comparison of fibre development in HC and LC refining and for comparison with SD-LC and DD-LC configurations.

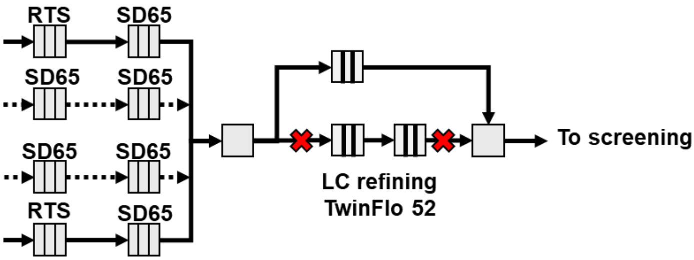

Figure 29. TMP3 in the Holmen Hallsta mill with two RTS-SD mainlines. The RTS refiners are Andritz SB170 units, all other HC refiners are Jylhä SD65. During one trial, Paper V, only the RTS refiner lines were in operation and that main line configuration is referred to as RTS-SD-LC-LC. Pulp sampling positions are marked with red crosses.

Interstage sulphonation in the RTS line

Trials with sodium sulphite addition to the RTS lines in Hallsta (referred to as RTS-S:SD) were conducted to compare the results with the application of sodium sulphite in the DD refining process in Braviken. Data from these trials have not been published previously. Different addition points were evaluated and here data is presented from a trial in which sodium sulphite (5 kg/adt, pH 9) was injected in the blow-line from one of the RTS refiners before the Perifeeder (steam separator) on the second stage SD refiner. The production rate in the RTS line was 16 adt/h and the specific energies in the refiners were 900 and 650 kWh/adt for the RTS refiner and the second stage SD refiner respectively. Pulp samples were taken from the blow-line after the second stage refiner.

7.5.2 Chip pretreatment prior to DD refining

In 2008, an Impressafiner (MSD 500, Andritz) was installed ahead of the three new parallel double disc refiners in Braviken, Figure 30. The Impressafiner has been used in earlier research (Nelsson 2015) as well as in the present work, Papers I and IV. A more detailed description of the process has been presented by Nelsson (2015). Only trials where the Impressafiner is utilized are denoted as containing chip pretreatment (CPT), as compared to the trial presented in section 7.4.4 and Paper VI in which sulphite was added before one of the DD refiners, immediately after the plug screw feeder, without using the Impressafiner.

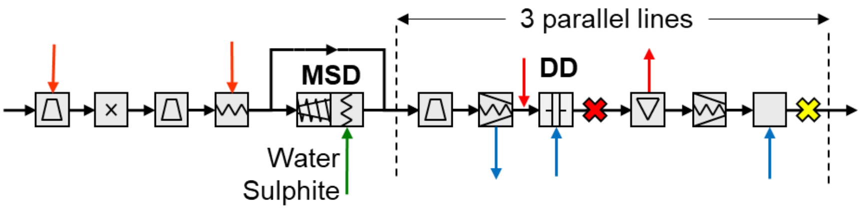

Figure 30. The DD line in the Braviken mill showing the Impressafiner (MSD 500) chip pretreatment which was possible to bypass. The section between the dashed lines consists of three parallel processes, *i.e.*, three DD refiners. Pulps for analyses were taken from the blow-line (red cross) and from the standpipes for production rate calculation (yellow cross). This process is referred to as the CPT-DD configuration.

The following configurations that include chip pretreatment have been evaluated in Braviken:

1. Mechanical chip pretreatment of chips and DD refining (Nelson *et al.* 2012, Paper I)
2. Low-dose sulphite chip pretreatment and DD refining (Nelsson *et al.* 2015, Paper I)
3. Sulphite chip pretreatment and DD refining with unidirectional (feeding) segments (Paper I).
4. Sulphite chip pretreatment, DD refining and LC refining (Andersson 2011, Paper IV)

A trial that included configurations 1-3 is described below whereas configuration 4 is described in section 7.5.2.

Chip pretreatment prior to DD refining with unidirectional segments (Paper I)

In this trial, chips were preheated, compressed in the Impressafiner and impregnated with water or sodium sulphite solutions, pH 9, using charges of 3.2 and 6.5 kg/adt (as Na_2SO_3). The applied specific energy in the Impressafiner was around 20 kWh/adt for all set-points. Pretreated chips were refined in two of the parallel DD refiners equipped with different segment types and operating at different production rates: One refiner had fine bidirectional segments operating at normal production rate (around 10 adt/h, at the time) and the other had unidirectional (feeding) segments operating at increased production rate (12.3 – 13.4 adt/h). As references, pulps were produced without Impressafiner chip pretreatment, with the two segment types. Detailed process conditions are presented in Paper I.

7.5.3 Combinations of HC and LC refining

LC refining has been an important part of this work and has had a role in most investigations, Papers II-VI, however with varying degree of focus. It is well known from earlier work, described in section 4.4.4, that LC refining requires lower specific energy compared to SD HC refining for a given increase in tensile index or reduction in freeness. However, in this work, the focus was on the role of LC refining in simplified process concepts and on how the pulp quality profile is affected by combinations of LC refining with different primary HC refiner types as well as on the fibre property development on a more detailed level than most earlier work.

The effect of HC primary refiner types (SD, CD, RTS and DD) on energy efficiency and pulp quality was evaluated for HC-LC refining during continuous operation or in shorter mill scale trials. Primary HC refiner pulps were refined in three LC refiner types; TwinFlo72 (TF72, Andritz) in the Braviken mill, TwinFlo52 (TF52, Andritz) in the Braviken and Hallsta mills and Conflo (CF82, Valmet) in the Stora Enso Kvarnsveden mill. In the study reported in Paper V, pulp samples were taken from HC refiners (CD, RTS-SD and DD) at two levels of SRE and after the subsequent LC refiners for the HC pulps with the lower SRE.

Two-stage LC refining was applied in the main line on DD and RTS-SD pulps as well as on rejects in the DD line in Braviken. Two-stage LC refining of rejects is not discussed in the thesis but is presented in Paper II. The most detailed studies of the effect on pulp and fibre properties are presented in Papers V and VI. The main line HC-LC combinations that were investigated are shown in Table 1.

Table 1. HC and LC refiner types and combinations in the studied main line process configurations.

HC	Type	LC Type	Paper
SD	RLP58	TF72	II, III
CD	RGP82CD	CF82	V
DD	RGP68DD	TF72	II, IV
DD	RGP68DD	TF52-TF52	VI
DD	RGP68DD	CF82	V
RTS-SD	SB170 - Jylhä SD65	TF52-TF52	V

7.5.4 High temperature DD refining with sulphite followed by two-stage LC refining

The combination of chip pretreatment with the Impressafiner and DD refining is an interesting combination for simplified processes. However, some drawbacks were identified in the early trials in Braviken including 50% loss of added sulphite in the plug screw feeders between the Impressafiner and the DD refiners as well as more unstable refiner operation, especially at increased production rate.

During the work for this thesis, Valmet developed new centre plates for the RGP68DD refiner, which was tested in Braviken, Paper VII. Initial trials with the new centre plate showed that it was possible to run the refiner at higher production rate and consistency than normal with lower motor load variations, whereas with the Impressafiner pretreatment, the motor load variations increased. It was therefore decided to perform trials with sulphite addition and using the new centre plate but without the Impressafiner.

S:HT:DDc-LC-LC (Paper VI)

Two trials made with the configuration shown in Figure 31 are presented in this thesis. Both trials were performed with the new centre plate at high production rate combined with high refining temperature (high housing pressure) and sodium sulphite addition, since earlier work had shown that sulphite treatment and increased refining temperature are additive (Nelsson *et al.* 2017). Process data are presented in Table A2, Appendix 2. With this configuration, pulp could not be pumped directly to the paper machine after LC refining, but still the aim was to reach final pulp quality for newsprint after LC refining.

The trials were made with one of the DD refiners in Braviken equipped with the new centre plate and coarse bidirectional segments that enabled a production rate around 18 adt/h at a motor load around 22 MW. The housing pressure was increased from 5 to around 6.6 bar(g). In both trials, 5 kg/adt sodium sulphite (pH 7.5) was added to the chips immediately after the plug-screw feeder. The sulphite pH was lower in this study since it results in somewhat higher brightness gain, which had become more important at the time of this trial. After the DD refiner, the pulp was pumped to the Twin 60 TMP line and LC refined in two-stages. During the trials, the screen rejects were fed to the HC rejects refiner. In the first trial, samples were taken before the first LC refiner as well as after both LC refiners. In the second trial, samples were taken before the first LC refiner and only after the second LC refiner. Pulps from the second trial was analyzed for more detailed fibre properties.

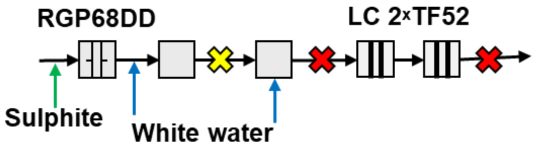

Figure 31. The configuration, referred to as S:HT:DDc-LC-LC, included DD refining at increased housing pressure and sodium sulphite added to the chips right before the refiner. After DD refining, the pulp was LC refined in two stages. Production rate was calculated from flowrate and consistency after the first dilution, marked with a yellow cross. Pulp samples for analyses were taken at the points marked by red crosses.

Reference process, SD-SD-LC-LC+SD (Paper VI)

The Twin60 line was used as reference for the second trial. Over time, the Twin60 line in Braviken has been improved by increased production rate, rearranged LC refiners from parallel to series refining and separate treatment of screen and hydrocyclone rejects, Figure 32.

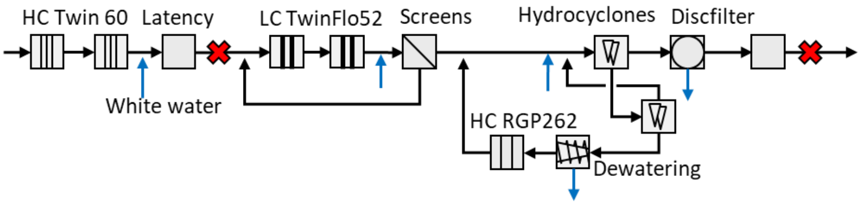

Figure 32. The Twin 60 line in Braviken used as reference process, denoted SD-SD-LC-LC+SD. Pulp samples for analysis were taken at the points identified by the red crosses. The production rate was 17 adt/h, calculated from flowrate and consistency after the latency chest.

Detailed fibre and pulp properties were measured on pulps sampled at the red crosses in Figures 31 and 32 in order to compare the simplified process concept with a more conventional process configuration involving advanced fractionation and rejects treatment.

This investigation also included a reference pulp from an RGP68DD refiner in Kvarnsveden, operating at relatively high production rate, 15.5 adt/h, see also section 7.4.1. The DD refiner did not have the new centre plate and was operated at lower housing pressure, 4 bar, with no sulphite addition.

7.6 Paper machine trials with simplified processes

The rejects handling system in a TMP process requires much equipment and energy and has been regarded as a crucial part of the mechanical pulping process, both for additional long fibre development and for shive reduction. However, over the years, some ideas have been presented to reduce the process complexity as described in section 4.6. and 4.7.

In this work two simplified process configurations have been evaluated in full scale on paper machines and in printing houses. The first configuration was used already in the RMP lines where screen rejects were circulated back to the second stage LC/MC refiner, see section 4.4.1. With this concept, referred to as "LC-F", no rejects thickening is needed. The second configuration combines Impressafiner chip pretreatment with sulphite impregnation followed by DD refining with feeding segments and subsequent LC refining.

7.6.1 HC-refining combined with LC refining and screen fractionation

Trials were made in Braviken to evaluate the LC-F process with two types of primary HC refiners, SD and DD, Figure 33, Paper III. New piping was installed in one of the three screen rooms to be able to feed screen rejects back to the chest before the LC refiner.

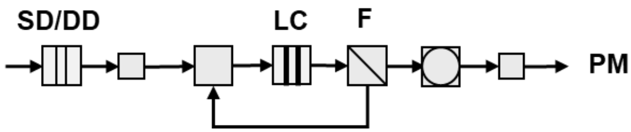

Figure 33. Schematic overview of the evaluated processes with screen rejects mixed with primary stage pulp before LC refining, referred to as the SD-LC-F and DD-LC-F configurations respectively.

Other rejects refining configurations have also been evaluated, Paper II, but they do not contribute to a simplified process and will not be discussed here.

Trial 1, DD-LC-F

When the first LC-F trial was made, the TF72 LC refiner was installed as the second stage refiner in the DD line in Braviken. The TF72 LC refiner has been described in more detail by Andersson (2011). For trial 1, Figure 34, denoted DD-LC-F, only one DD refiner was in operation at a production rate of 10.5 adt/h, but the production rate to the LC-F system was 15 adt/h (*i.e.*, the level decreased in the pulp tower after the DD refiners). This was necessary in order to achieve an appropriate production rate to the screens. Process conditions are presented in Paper III. After main line refining, the pulp was screened and the accept pulp bypassed the hydrocyclones to the disc filters and further on to the paper machine during standard newsprint production. Screen rejects were fed back to the chest before the LC refiner.

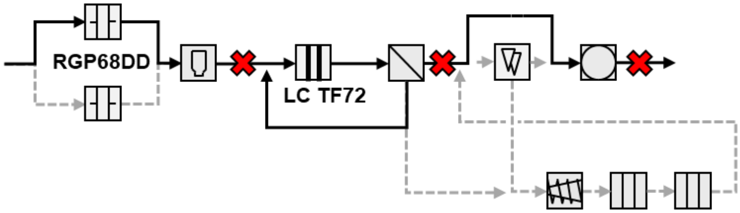

Figure 34. The DD-LC-F process configuration for trial 1. During the trial, only one of the two DD refiners was in operation and the hydrocyclones and HC rejects refiners were bypassed. Sampling points are marked with red crosses.

Trial 2, SD-LC-F

Later, the TMP mill was restructured and the LC refiner and rejects system shown in Figure 34 was supplied with pulp from the four parallel primary stage RLP58 refiners. The refiners were supplied with a similar chip-mix as in the first trial.

In this trial, three of the four primary RLP 58 refiners were in operation which rendered a production rate of 12 adt/h. The RLP 58 refiners were manually adjusted to the set-point for blow-line freeness and consistency. For this trial, screen accepts were not by-passing the hydrocyclone system since it was anticipated that the shive content would be too high. Pulp samples were taken from the mixed HC primary refiner pulps and the screen accept.

7.6.2 Chip pretreatment prior to DD refining and LC refining

During the early work associated with the DD line in Braviken (Muhic 2010, Andersson 2011, Nelsson 2016), it was noted that the pulp after main line refining exhibited properties close to the final pulps, *i.e.*, after the rejects treatment systems, of the two-stage SD TMP lines. Based on this insight, planning of trials with a simplified process without any rejects treatment was initiated, Paper IV. Piping was installed after the TwinFlo72 LC refiner that made it possible to by-pass the screens, hydrocyclones and disc filters.

In this trial, denoted CPT:S-DDu-LC, with the configuration shown in Figure 35, chips were pretreated with sodium sulphite (6.5 kg/adt, pH 9) that was added to the impregnator after the Impressafiner (MSD). Two DD refiners were equipped with unidirectional (feeding) segments which enabled an increased production rate from 22 to 31 adt/h. After refining, the pulp was diluted and fed to a Twin-roll press and afterwards diluted with PM white water before LC refining in the TF72 refiner. After LC refining, the pulp was pumped to the paper machine without any further treatment. After a few hours of initial adjustments, the paper machine ran for four hours using the trial pulp. The produced paper was evaluated in printing houses.

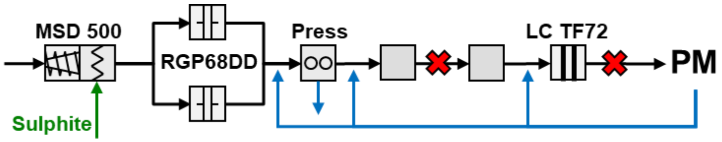

Figure 35. Overview of the simplified process with Impressafiner chip pretreatment (MSD), DD refining and LC refining, referred to as the CPT:S-DDu-LC configuration. After LC refining, the pulp was pumped directly to the PM.

Reference samples were taken from the final pulp of the SD TMP line that normally supplied the paper machine at the time. The configuration is shown in Paper IV and was similar to the TMP line supplying PM52 today (2022) shown in Appendix 1.

8 Results and discussion

The goals of this work were to reduce the specific energy and to reduce the number of unit operations required to produce a pulp with adequate quality and runnability for use in printing papers. The presentation of the results is structured based on these two goals, rather than in chronological order of the trials.

The first sections of this chapter cover the choice of how the results are presented, 8.1, and the reference processes used, 8.2. Thereafter, the effect of process configurations on energy efficiency, 8.3, and pulp properties, 8.4, is presented. LC refining has been an important part of this work and some results, that does not fall within sections 8.3 and 8.4, are presented in section 8.5.

The change from SD refiners to DD refiners in 2008 in one of the TMP lines in the Braviken mill had a remarkable effect on the paper quality from PM51 which produced directory paper at the time. Data from the transition have never been published before, but these data are highly interesting for the understanding of how fibre properties affect the produced paper on a paper machine. Therefore, some data from this change is presented in section 8.6. In section 8.7, paper machine trials with simplified processes are presented.

8.1 Presentation of results

In the thesis, I have chosen to present selected process configurations from Papers I to VII that contribute to the goals of this work – reduced process complexity and reduced specific energy demand. Based on the discussion in section 6.3.1, I have chosen to relate specific energy reduction to tensile index, while trying to maintain acceptable light scattering, shive content and average fibre length. The effects of process design on these pulp properties are presented in section 8.4. However, the work presented in Papers V and VI, include more detailed studies of the fibre morphology aimed at providing a deeper understanding of how some refiner combinations affect the pulp quality. It is of course a prerequisite to maintain the performance of the final product and therefore pulp from two simplified process configurations were evaluated on paper machines in Braviken, section 8.7. It is nearly impossible to attain exactly the same paper quality with different process configurations, which might not necessarily be preferable to strive for in some cases. This issue is discussed in section 8.6.

Data presentation in graphs

The notations used for all process configurations in the text and in the legends of the graphs are provided in section 7.1.

The following symbols are used for data representation in graphs:

□ SD, RLP/RL 58, single and two-stage, Braviken

■ SD, Twin 60, two-stage, Braviken

■ Final pulp for newsprint from an RLP58 TMP line in Braviken, base reference

○ DD, RGP68DD, single-stage, Braviken, 10-18 adt/h

⊗ DD, RGP68DD, single-stage, Kvarnsveden, 11 adt/h

⊕ DD, RGP68DD, single-stage, Kvarnsveden, 15.5 adt/h

◇ RTS-SD, SB170 2300 rpm - Jylhä SD65 1500 rpm, Hallsta, 12-16 adt/h

△ CD, RGP82CD 1800 rpm, single stage, Kvarnsveden, 13 adt/h

+ Final pulp, BAT TMP lines, from Ferritsius et al. (2014)

□ Thick outline = Outlet sample from an LC refiner, here with SD HC refined pulp as feed

⁘ Dashed outline = Wood chips were pretreated with an Impressafiner

○ Red outline = Increased refining temperature (housing pressure)

When more than one sample was taken in a study, for example a refining curve (samples taken at the same position at different conditions, *e.g.*, gap or production rate) or when samples were taken in more than one position, the points in graphs are connected with lines. The connecting lines between points in graphs do not represent physical relationships, they are only used to make it easier to read the graphs. The following connection line types are used:

——— Refining curve, samples taken from the outlet of one refiner

– – – – Feed and outlet samples from a 2nd stage HC refiner

- - - - - - - - Feed and outlet samples from an LC refiner

– · – · – Samples before and after a reject system

The types of data are illustrated in Figure 36.

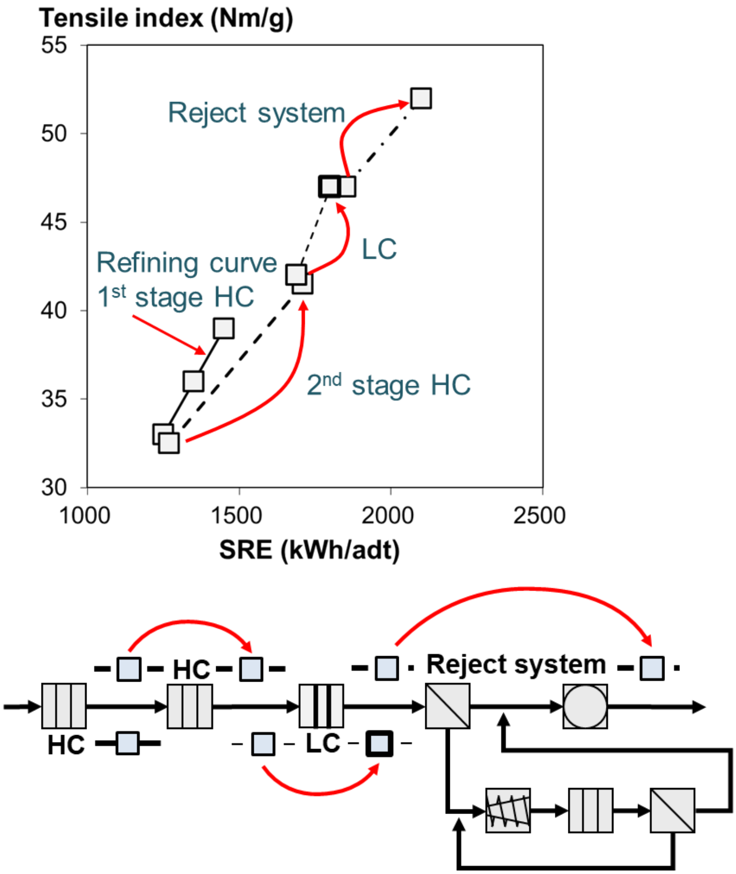

Figure 36. Examples of sample points and corresponding data presentation in graphs. The data in the graph (**top**) are not from an existing TMP line, it only illustrates the sample positions in the process (**bottom**).

In two trials, the wood chips were pretreated with an Impressafiner, denoted CPT, before DD refining. The Impressafiner was followed by impregnation with only water, CPT:W, with the symbols filled light blue, or with a sodium sulphite solution, CPT:S, symbols filled yellow. For the trials where the Impressafiner was used, the DD symbols in the graphs have a dashed outline.

In two other trials, sodium sulphite was added to the wood chips or the pulp immediately before the refiners which is indicated by an S before the refiner notation, S:DD and RTS-S:SD, and those symbols are also filled yellow.

8.2 Reference processes

At the beginning of this development work, the TMP lines in the Braviken and Hallsta mills had two-stage SD HC refining in the main line and SD HC rejects refining, however, with somewhat different screen room and rejects refining configurations, section 7.2. These processes performed in a rather similar manner in terms of specific energy demand and pulp quality development. At the start of this work, LC refining had been installed in two of the three TMP lines in the Braviken mill, as shown in Figure 27 and in one of the TMP lines in Hallsta, as shown in Figure 29.

Over time, the specific refining energy has been reduced for the TMP lines in Braviken and Hallsta by successive installation of LC refining, RTS and DD refiners as well as by increased production rate and segment design development. Therefore, different process configurations have been used as references in the trials in this work.

In Figure 37, results from earlier work in Braviken are shown (Muhic *et al.* 2010, Andersson *et al.* 2012a, Nelsson *et al.* 2015) together with average data for the final pulp from one of the newsprint TMP lines, SD-News, which is shown in Figure 27 (top).

The main line pulps (HT:DD, DD-LC and CPT:S-DD) from the earlier research work have similar tensile indices and shive contents compared to the SD News pulp, *i.e.*, after fractionation and rejects refining. This observation was the starting point for the research on simplified process concepts as presented in this thesis. Since all three concepts seemed interesting and the combination of them had not been evaluated, it was decided to continue the work with all three.

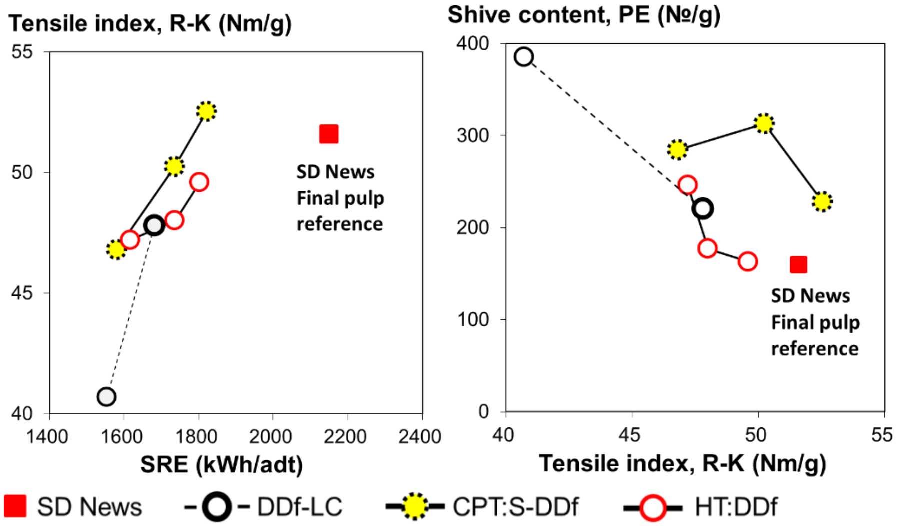

Figure 37. Data from earlier work in Braviken by Muhic *et al.* (2010), Andersson *et al.* (2012a) and Nelsson *et al.* (2015). Main line refiner pulps from the DD-line before screening required lower specific refining energy (SRE) and exhibited tensile index (**left**) and shive content, PulpEye, PE, (**right**) in the same range as the final pulp (SD News) from the TMP line shown in Figure 27 (top). The "SD News" point represents a one-year averages of over 100 samples. Tensile index was measured on Rapid-Köthen (R-K) handsheets. The DDf-LC points are averages of several samples taken before and after the TF72 LC refiner in the DD-LC configuration.

8.3 Specific energy

In this section, the electrical energy demand for the investigated process configurations is presented. The specific refining energy (SRE) is calculated from the total (gross) refiner power and the production rate. The specific energy is presented in kilowatt-hours per air-dry (90% dry content) metric tons (kWh/adt). Since the auxiliary electrical energy is also reduced when the process complexity is reduced, the total specific energy is presented for some trials.

The term "energy efficiency" is used frequently in this work referring to the specific energy required to reach a given tensile index. Thus, a high energy efficiency means a low specific energy required to reach a given tensile index.

Sodium sulphite has been added to several of the evaluated processes in this work. Adding 5 kg/adt sodium sulphite to the process implies an additional cost that corresponds to approximately 70 kWh/adt in electrical energy (in

Sweden 2021). This "additional energy" is not included in the data shown in the graphs, but should be kept in mind.

DD refiners require a supply of steam to the chip feed side of the refiner. This is usually clean steam which, in the Braviken mill, is produced in a bio-fuel boiler. Most of the energy in this steam is recovered in the reboiler but clean boiler water is lost from the steam system, and this must be replaced. The cost for this make-up water corresponds to a specific energy of around 40 kWh/adt in Braviken in 2021.

8.3.1 Main line configurations

HC refining (Papers I-VII)

Five main line HC refiner configurations have been studied in this work:

1. SD Single-stage SD HC refining
2. SD-SD Two-stage SD HC refining
3. RTS-SD Two-stage SD HC refining, primary 2300 rpm
4. CD Single-stage CD HC refining, 1800 rpm
5. DD Single-stage DD HC refining

In Figure 38, tensile index measured on Rapid-Köthen handsheets is shown versus specific refining energy (SRE) for the main line HC refiner types that have been investigated in this work. The DD refiners (RGP68DD) in Braviken and Kvarnsveden were sampled at different disc-gaps at their normal production rate at the time (around 10-11 adt/h). At a tensile index of 50 Nm/g, as measured on R-K handsheets, the SRE for the DD refiners is around 300 kWh/adt lower than for SD-SD refining, which is similar to earlier studies, section 8.2. Later, both Braviken and Kvarnsveden changed from fine bidirectional segments to a more open bidirectional design that enabled higher production rate. As an example, data for a DD refiner in Kvarnsveden operating at 15.5 adt/h is shown (DDc K 15 t/h). The DD refiner in Kvarnsveden reached a tensile index of 49 Nm/g, close to the SD News final pulp, at just below 1500 kWh/adt, which is very efficient. The experience from both Kvarnsveden and Braviken is that for every ton per hour in increased production rate over the RGP68DD refiners, the SRE is reduced by around 50 kWh/adt.

The RTS lines (SB170+Jylhä SD65) in Hallsta were also studied and pulp samples were taken after the second stage SD refiners (mixed pulp from both lines) at two production rates, 12 and 14 adt/h for each of the two lines, Paper V. The RTS-SD configuration showed a performance similar to the DD refiners operating at 10-11 adt/h. A second high speed HC refiner was included in the study reported in Paper V; the 1800 rpm CD82 refiner in Kvarnsveden. The CD82 was operating as single-stage HC refining followed by an LC refiner, see below, and was sampled at two levels of dilution water flow into the flat zone. At a given SRE, the CD refiner yielded pulps with a similar tensile index compared to the SD refiners.

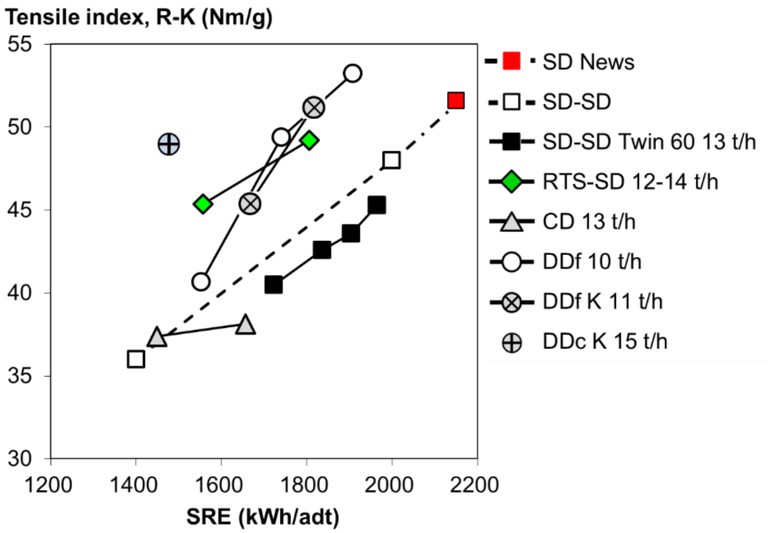

Figure 38. Tensile index measured on Rapid-Köthen handsheets versus specific refining energy for four HC refiner main line configurations. "SD-SD" are pulps from primary and secondary stage HC refiners respectively in the RLP58 line, Figure 27 (top). The final pulp from the same TMP line, "SD News", is highlighted with red fill, since it represents the pulp properties aimed for in this thesis. "SD-SD Twin 60" is a refining curve from the second stage HC refiner in the Twin 60-line shown in Figure 27 (bottom), obtained by changing the disc gap at a constant production rate of 13 adt/h production rate. The "RTS-SD" are mixed pulps sampled at two production rates, 12 and 14 adt/h from each line, after the second stage SD refiners in the RTS line in the Hallsta mill, Figure 29. Two points are shown from the 1800 rpm CD82 single-stage HC refiner in Kvarnsveden at two flowrates of dilution water to the flat zone. The RGP68DD refiners in Braviken and Kvarnsveden, equipped with fine bidirectional segments (DDf), were sampled at different disc-gaps at their normal production rate at the time (around 10-11 adt/h). Also, data from a RGP68DD refiner in Kvarnsveden equipped with coarse bidirectional segments (DDc) operating at 15.5 adt/h are shown.

One-year average data from one of the SD TMP lines in Braviken, with the configuration shown in Figure 27 (top) and denoted SD-SD+SD-LC, are included as a base reference in the figures below. The three data points represent pulp samples taken in the positions marked with red crosses in the figure; mixed pulps from the four primary refiners, the three secondary refiners and the final pulp respectively. The final pulp from this TMP line is highlighted with red fill and is denoted “SD News”. A refining curve from the second stage HC refiner in the Twin 60-line shown in Figure 27 (bottom) is also included.

Clearly, a tensile index similar to the final pulp for newsprint (SD News), after screening and rejects refining, can be reached with single-stage DD refining but at lower SRE. Note that an increase in SRE attained by reduced disc gap, has a much larger effect on tensile index for DD refiners (steeper slope) than for second stage SD refining. Therefore, it is important to operate DD refiners at as small a disc gap as possible – however too small a gap will reduce the fibre length significantly, see section 8.4.4.

Chip pretreatment ahead of DD refining with unidirectional segments (Paper I)

The effect of mechanical chip pretreatment followed by water or sodium sulphite impregnation was evaluated for two segment designs: fine bi-directional, DDf, and unidirectional (feeding), DDu, in the DD refiners in Braviken, section 7.4.2. The unidirectional segments enabled an increased production rate from 10 to 13 adt/h, which resulted in 150 kWh/adt lower SRE to a given tensile index compared to operation with fine bidirectional segments at 10 adt/h, Figure 39. In this trial, chip pretreatment with the Impressafiner followed by water impregnation did not affect the SRE. Earlier mill scale work with Impressafiner pretreatment (no sulphite) resulted in around 100 kWh/adt lower SRE, but that was with a higher compression ratio than in the present study (Sabourin *et al.* 2001, Nelsson *et al.* 2012). Therefore, it can be concluded that it is necessary to reach a certain degree of mechanical pretreatment of the wood chips to attain an effect on the refining energy required to reach a given tensile index.

The combination of feeding segments at increased production rate (13.4 adt/h) and chip pretreatment with 6.5 kg/adt sodium sulphite, pH 9, (CPT:S-DDu), reduced the specific energy by around 300 kWh/adt compared to the DD refining reference and by 600 kWh/adt compared to the final pulp for news (SD News). At the low charge levels used in this work and in the work by Nelsson (2016), addition of sodium sulphite before or in the refiner have resulted in an increase in tensile index at a given SRE of around 1 Nm/g per 1 kg/adt sulphite (pH 7-9).

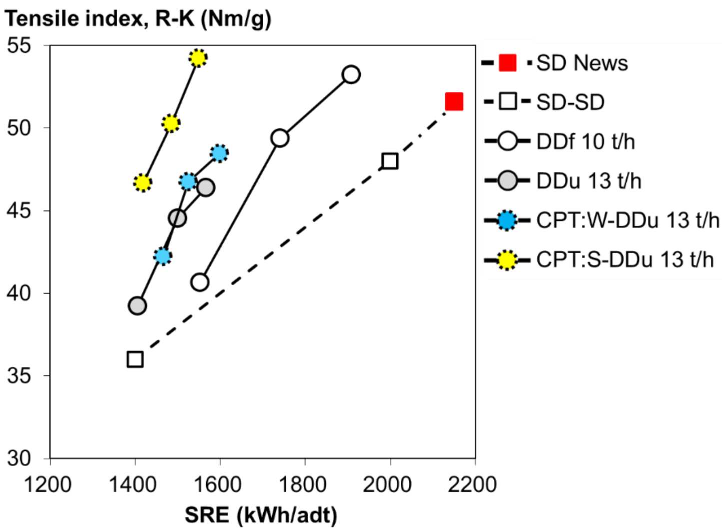

Figure 39. Chip pretreatment followed by water impregnation (CPT:W) or sodium sulphite impregnation (CPT:S) prior to DD refining with unidirectional (feeding) segments (DDu), reduced the specific refining energy compared to DD refining with fine bi-directional segments and no chip pretreatment (DDf). The DD refining curves were generated by changing the disc gap.

This effect is seen in Figure 39, comparing the data for CPT:S-DDu and CPT:W-DDu. It should be noted that some of the sodium sulphite added after the Impressafiner is removed in the plug-screw feeders before the refiners (Nelsson 2016).

<u>Combinations of high and low consistency refining (Papers II-VI)</u>

Four combinations of main line HC refining and LC refining have been evaluated, section 7.4.3:

- SD-LC — Braviken, Papers II and III
- CD-LC — Kvarnsveden, Paper V
- RTS-SD-LC-LC — Hallsta, Paper V
- DD-LC/DD-LC-LC — Kvarnsveden: Paper V, Braviken: Papers II, III, IV and VI

The tensile index increase at a given SRE applied in the LC refiners was similar for all types of feed pulp and refiner types, Figure 40. The required specific energy for LC refining was around 50% lower than that required for SD HC refining. However, when disc gap is used to change the SRE, the DD refiners yield similar slopes as for LC refining, one example shown in Figure 40. During the initial work with the DD-LC process in Braviken (Andersson 2011), the DD refiners were operated at increased disc gaps, and maintained production rate. This improved the total efficiency only marginally. In later work reported in Papers IV and VI, the production rate was increased, and disc gap maintained which increased the total efficiency. Therefore, as long as the load can be increased in a DD refiner, it is not more efficient to substitute that load with LC refining.

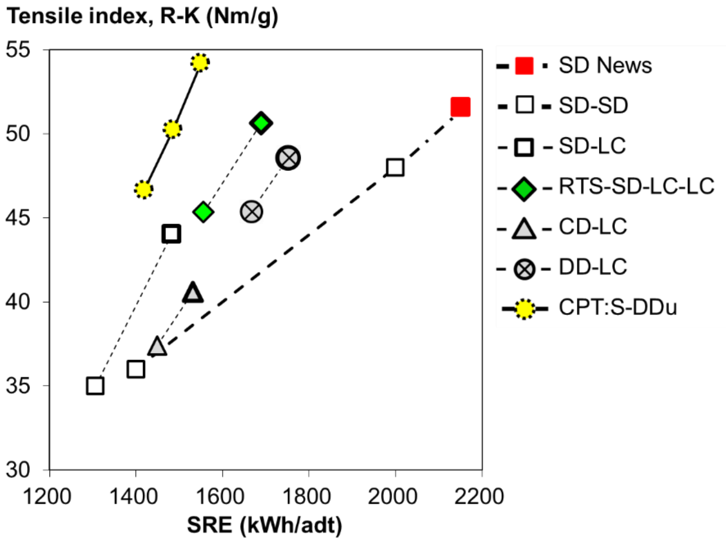

Figure 40. For a given SRE, all LC refiners result in similar tensile index increases which are around twice as high as for a second stage SD HC refiner, thick dashed line. Feed and outlet samples, connected by thin dashed lines, from the LC refiners are shown with the outlet points having a thick outline. LC refining of DD pulp at the Braviken and Kvarnsveden mills gave similar responses, however, in this graph only data from Kvarnsveden is shown. When the SRE is increased in DD refiners by reducing disc gap (one example from Figure 39 is shown, CPT:S-DDu), the tensile index increase is similar to that achieved by LC refiners.

With single-stage LC refining, at the normal production rates for the SD-LC line (17 adt/h) and for the CD-LC line (13 adt/h), the tensile index level corresponding to final pulp for news (around 50 Nm/g) was not reached. With the RTS-SD-LC-LC process, that tensile index level could be reached at a SRE that was more than 400 kWh/adt lower than the SD News final pulp. The DD-LC processes could have reached the SD-News level if somewhat higher SRE had been applied in the DD refiners. More data from the study of HC and LC refining, reported in Paper V, is found in Table A1, Appendix 2. LC refining is discussed further in section 8.5.

A comparison of the effect of LC refining in the main line and the rejects line was also made, see Paper II for details. It was concluded that main line application is advantageous taking into account the maximum applied specific energy, flow rates and machine size. Moreover, since one of the goals of this work was to reduce the process complexity, the main line position is clearly advantageous.

Inter-stage sulphonation in the RTS line

The data from this trial has not been published previously, but was considered interesting to include for comparison with the work with sulphite addition in the DD line in Braviken. The effect of sulphite addition was evaluated for the RTS process in the Hallsta mill, denoted RTS-S:SD, section 7.4.1. The sodium sulphite (5 kg/adt, pH 9) was added in the blow-line from the RTS refiner, just before the second stage SD refiner. This concept resembles the old "Interstage sulphonation" process (OPCO process) but in that process the primary stage pulp was digested with a much higher dose of sulphite than in the present study for 15-120 min (Barnet *et al.* 1980). The RTS-S:SD process required around 250 kWh/adt lower SRE to reach a given tensile index than the RTS process without sodium sulphite, Figure 41. No samples were taken after the proceeding LC refiners during the sulphite trial since the RTS pulp was mixed with pulp from the SD-SD lines before the LC refiners.

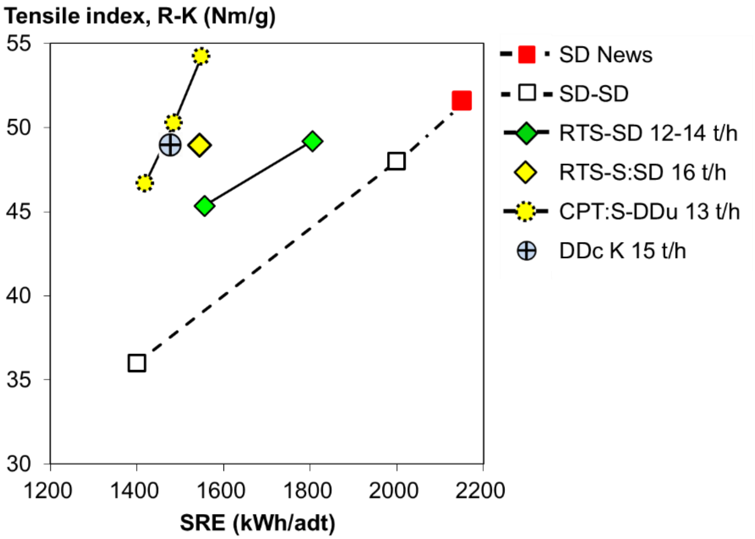

Figure 41. The RTS-S:SD process is relatively efficient. With higher production rate and combined with LC refining, it would likely reach a similar efficiency as the DD processes.

High temperature DD refining with sulphite followed by two-stage LC refining (Paper VI)

In these two trials, described in section 7.4.4, sodium sulphite (5 kg/adt, pH 7.5) was applied to a DD refiner without chip pretreatment. Instead, the sulphite was added immediately after the plug screw feeder, around 8 seconds before the refiner. Additionally, the DD refiner housing pressure was increased from the normal 5.0 to around 6.6 bar(g) and the production rate was increased from 13 adt/h to around 18 adt/h which was possible due to the new centre plate described in Paper VII. After the primary DD refiner, the pulp was refined in two TF52 LC refiners arranged in series. With this configuration, the pulp could not be fed directly to the paper machine, due to lack of piping. However, the main purpose of the trials was to study the fibre development in more detail, section 8.4.

The SRE for the S:HT:DDc-LC-LC process was just below 1300 kWh/adt in the first trial and 1400 kWh/adt in the second trial, which is 600-700 kWh/adt lower than the reference process (SD-SD-LC-LC+SD) compared at tensile index 53 Nm/g (interpolated), Figure 42. The SD-SD-LC-LC+SD process required lower SRE to a given tensile index than that shown in Figure 38 for the same Twin 60 refiners, mainly due to increased production rate and new segment design.

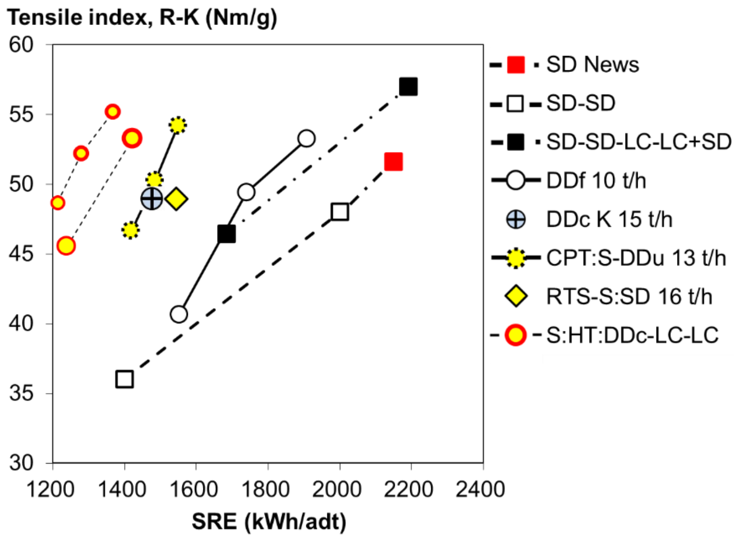

Figure 42. The SRE required to reach 53 Nm/g tensile index was 600-700 kWh/adt lower for the S:HT:DD-LC-LC process than the SD-SD-LC-LC+HC reference (interpolated). The first S:HT:DD-LC-LC trial, in which pulp was sampled also after the first LC refiner, is shown with small symbols.

Data from some of the processes presented above are included in the graph for comparison. The higher housing pressure and production rate compared to the CPT:S-DDu configuration reduced the SRE by around 200 kWh/adt, depending on which level of tensile index the comparison is made. The SRE reduction compared to SD TMP for this trial is similar to the level reported by Sabourin (2007) for a CPT-RTS-LC process evaluated in pilot scale and 15% lower than mill scale results from an ATMP (CPT-S:RTS-SD-LC+SD-LC) process (estimated from the limited data reported by Radhuber *et al.* (2016)).

8.3.2. Simplified process configurations evaluated on paper machines

Practically all TMP processes contain a rejects treatment system that has been regarded as an essential section of the mechanical pulping process, both for additional long fibre development and for shive reduction. However, this additional treatment requires much equipment and energy.

In this work two simplified process configurations have been evaluated in full scale on paper machines and in printing houses. Results from the paper machine trials are presented in section 8.7 whereas the specific energy demand is presented in this section and the pulp quality in section 8.4. In the first configuration, screen rejects were circulated back to the second stage LC refiner and thereby no rejects thickening, or HC rejects refining were needed. The second configuration consisted of Impressafiner chip pretreatment with sulphite impregnation followed by DD refining with feeding segments and subsequent LC refining.

<u>HC refining combined with LC refining and Screening (Paper III)</u>

The process consisting of single-stage HC refining, followed by LC refining and screening, denoted HC-LC-F was evaluated with two HC primary refiner types, SD and DD, section 7.5.1. After LC refining, the pulp was screened, and the rejects were fed back to the LC refining. This combination of LC refining and screening was utilized early for mechanical pulp production, section 4.4.1. However, to my knowledge, the effect on efficiency and pulp quality of the preceding chip refiner type has not been studied.

In Figure 43, tensile index versus SRE is shown for only LC refining (SD-LC and DD-LC) and for the two HC-LC-F processes. During the SD-LC-F trial, only three out of four RLP58 HC refiners were in operation, and thus the production rate was lower than for SD-LC refining. In addition, the specific energy in the SD refiners and thereby also the tensile index was somewhat higher in the SD-LC-F trial. The low production rate resulted in higher specific energy in the LC refining stage and therefore in a larger tensile index increase over the LC-F system than for LC refining alone. Thereby, the tensile index of the screen accepts was closer to that of the final pulp for news, but still lower than for the process using DD primary refining.

Since the tensile index was considerably higher from the DD refiners, a final tensile index level corresponding to the SD News was reached for the DD-LC-F process. At a given tensile index, there was no difference in SRE between the DD-LC and DD-LC-F processes, both had around 400 kWh/adt lower SRE than the SD News. The auxiliary specific energy was almost 100 kWh/adt lower for the LC-F processes than for a normal rejects system using HC refining, since five unit operations, three chests and a number of pumps were not required. Thus, the total specific energy for the DD-LC-F process was around 500 kWh/adt lower than the final pulp for newsprint (SD News). During the DD-LC-F trial, the screen accepts bypassed the hydrocyclones and were fed directly to the disc filter and further on to the paper machine. Newsprint was produced and printed for evaluation of the process, section 8.7.

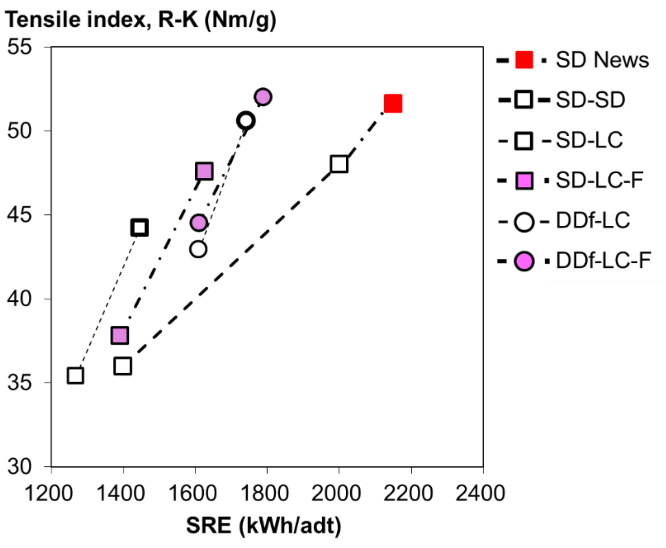

Figure 43. Comparison of LC refining (thin dashed lines) and LC refining combined with screening (dash-dot lines) for SD and DD feed pulps, data from Paper II and III. The efficiency η (see section 6.2) was slightly lower for the LC-F process than for LC refining alone. For the two LC-F series, samples were taken after the HC refiners and from the screen accepts, connected by dash-dot lines. For LC refining alone, feed and outlet samples are shown, connected by thin dashed lines.

The LC-F systems had slightly lower efficiency, as defined in section 6.2, than LC refining alone, η = 42 and η = 54 (Nm/g)/(MWh/adt) respectively. In this comparison of HC-LC-F processes with different primary HC refiner types, the SD-LC-F configuration required somewhat lower SRE to a given tensile index. To reach the tensile index level of the SD News pulp, more energy in the SD HC refiners is needed, which would have reduced the efficiency and the production rate. Moreover, the SD-LC-F process rendered a pulp quality that was less attractive, mainly due to high shive content and low light scattering coefficient, section 8.4. It should also be noted that the DD-LC-F trial was made at a time when the production rate for the DD refiners was low, 10-11 adt/h, and as a consequence also the energy efficiency.

Chip pretreatment followed by DD refining and LC refining (Paper IV)

A second simplified process was evaluated in the Braviken mill. The process is denoted CPT:S-DDu-LC and consisted of chip pretreatment using the Impressafiner followed by impregnation with 7.2 kg/adt sodium sulphite (pH 9), section 7.5.2. The impregnated chips were refined in two of the DD refiners equipped with unidirectional (feeding) segments. The produced pulp was further refined in the TF72 LC refiner and thereafter fed directly to the paper machine (PM52). The use of unidirectional segments in the DD refiners during the trial enabled a 40% increase in production rate.

The SRE was around 750 kWh/adt lower than the reference process which performed quite similar to the SD News process, Figure 44, and 450 kWh/adt lower compared to the best available technology (BAT) in Scandinavia at the time (Ferritsius *et al.* 2014).

The energy demand for auxiliary equipment was 120 kWh/adt, which was less than half of that for the reference TMP line and thereby the total specific energy was around 900 kWh/adt lower than for the SD News process. The simplified process required a considerably lower number of unit operations compared to a conventional TMP line, as well as a lower number of pumps, chests and other auxiliary equipment.

The lower SRE (around 100 kWh/adt) for the CPT:S-DDu-LC process compared to the CPT:S-DDu process is mainly an effect of the increased production rate, from 13 to 15.5 adt/h, made possible by the LC refining stage.

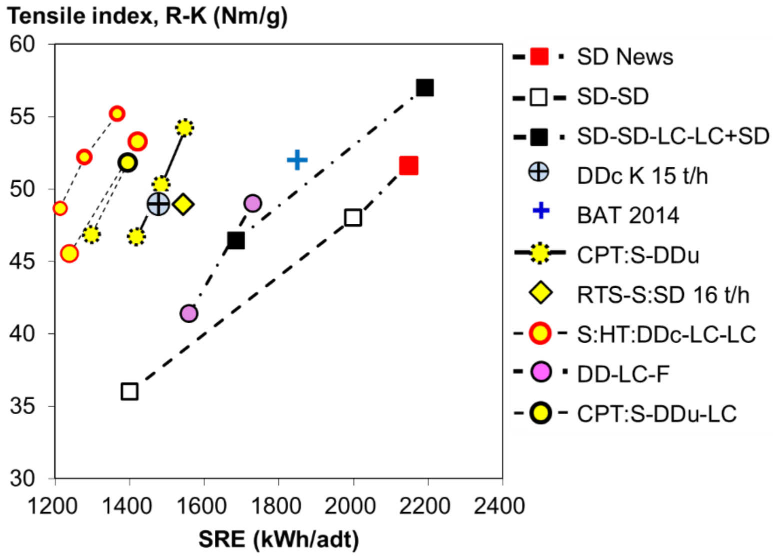

Figure 44. The specific refining energy for the simplified process, CPT:S-DDu-LC, was 750 kWh/adt lower compared to the final pulp for newsprint in Braviken, SD News, and 450 kWh/adt lower compared to best available technology (BAT) in Scandinavia (2014). The pulp samples were taken before and after the LC refining stage. The BAT data are based on data from Ferritsius *et al.* (2014) recalculated to Rapid-Köthen tensile index.

The efficiency of the CPT:S-DDu-LC process was similar to the second trial with the S:HT:DDc-LC-LC process, but the pulp quality was not the same, section 8.4. The SRE for the two-stage LC refining in the S:HT:DD-LC-LC trial was higher than for the single-stage LC refining and therefore also the tensile index increase was larger.

8.3.2 Energy efficiency summary

Several process concepts have been evaluated in which different means have been used to reduce the specific energy. In Table 2, the average specific energy reductions attained for the approaches studied in this work (see section 7.3) are shown. All effects are not additive and in processes other than those studied, the effects may be different.

The two approaches that have the largest effect on energy efficiency (expressed as SRE required to reach a given tensile index) are, high intensity refining (DD and RTS) and increased production rate. For every ton per hour in increased production rate over the RGP68DD refiners, the SRE is reduced by around 50 kWh/adt. The highest efficiency for main line HC refining was attained with single-stage DD refining.

The lowest SRE, 1280 kWh/adt at 52 Nm/g tensile index (R-K), was attained in one of the trials with the S:HT:DD-LC-LC configuration. This is around 900 kWh/adt lower SRE compared to the final pulp for newsprint based on SD HC refining, and 600 kWh/adt lower compared to Scandinavian BAT processes (Ferritsius *et al.* 2014). Additionally, the auxiliary energy is around 150 kWh/adt lower for a process without screening and HC rejects refining.

Table 2. Average specific energy reductions to a given tensile index attained for the approaches studied in this work compared to a SD TMP process.

Method	Potential reduction (kWh/adt)
Impressafiner chip pretreatment (without sodium sulphite)	0*
Addition of low doses of sodium sulphite (around 5 kg/adt)	200
DD and RTS compared to SD	300**
Single- versus two-stage refining	0
Segment and centre plate design	Connected to prod. rate
Increased production rate 10 to 18 adt/h (DD refiners)	300
High refining temperature (housing pressure 6.6 bar)	100
LC refining (compared to SD HC refining)	150

* In earlier reported studies with the Impressafiner (Nelsson *et al.* 2012) the mechanical chip pretreatment resulted in an SRE reduction of around 100 kWh/adt, but in those trials the compression ratio was higher in the Impressafiner

** The 300 kWh/adt is valid both for comparison between DD refiners at 10-11 adt/h production rate and the SD refiners at the time, but also for DD refining at high production rate (DDc K 15 t/h) compared to the improved SD-SD-LC-LC+SD process.

Other interesting processes with relatively high efficiency were Impressafiner pretreatment of the wood chips with sodium sulphite before DD refining, with or without proceeding LC refining, RTS primary refining with sodium sulphite added before the second stage SD refiner and finally, a single-stage DD refiner operating at relatively high production rate, 15.5 adt/h, and 4 bar housing pressure (no sodium sulphite).

The auxiliary energy was around 150 kWh/adt lower for simplified processes than TMP lines with conventional fractionation and rejects refining systems.

8.4 Pulp quality

In this section, the characteristics of pulps produced with the different process configurations is presented. Based on the discussion in section *6.3.1., shive content, light scattering coefficient and average fibre length are presented for pulps from all configurations. For the trials reported in Papers V and VI, more detailed fibre analyses were made to gain an increased understanding of differences in fibre development in HC and LC refining and also of the fibre development in one of the studied configurations intended for simplified processes. More data from those two studies are presented in Appendix 2.*

8.4.1 Shive content

As mentioned in sections 3.5 and 6.3.1, the shive content is an important pulp property, which certainly limits the possibility to simplify the process. In Figures 45 A-D, the shive content (total number of shives per gram, PulpEye) for the studied process configurations is shown versus R-K tensile index. In this work, the goal was to reach a shive content of 200 shives/g (PulpEye) which is the average level for newsprint pulp in Braviken.

In Figure 45 A, shive content for the HC refiner configurations is shown. Generally, DD and RTS refiners render pulps with lower shive content than the SD and CD refiners. Interestingly, the DD refiner in Kvarnsveden operating at normal refining temperature (4 bar housing pressure) and no sulphite addition (DDc K 15 t/h) produced pulp with a shive content lower than the final pulp for newsprint (SD News). Often, increased production rate leads to unchanged or increased shive content at a given freeness or tensile index (Strand *et al.* 1993, Stationwala *et al.* 1994, Murton and Corson 1997) whereas for the RGP68DD refiner, the shive content is considerably reduced.

The shive reduction over the LC refiners varied and was lower or similar to that attained with HC refining to a given increase in tensile index, Figure 45 B.

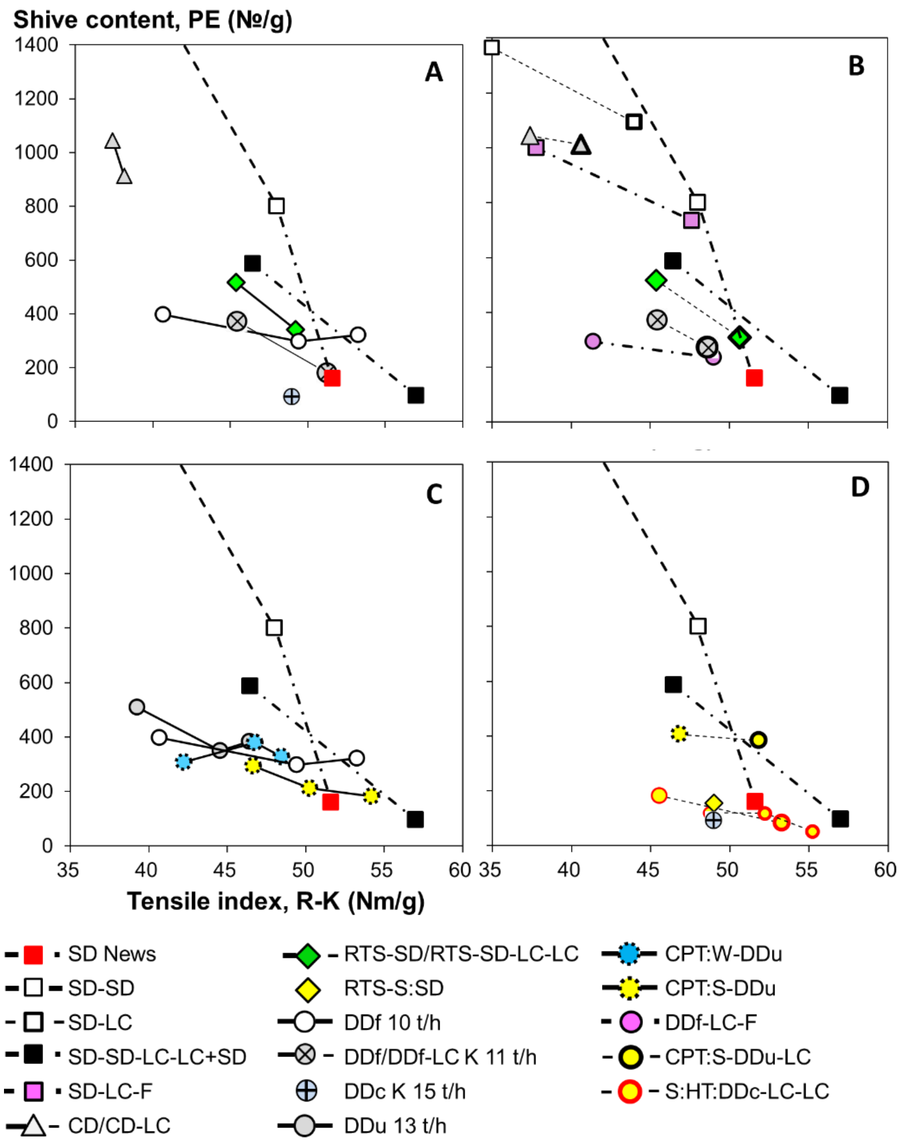

Figure 45. The shive content PE (PulpEye), measured as the total number of shives/g, versus tensile index for the studied configurations. **A:** DD and RTS refiners yielded pulps with lower shive content than the SD and CD refiners. **B:** The shive reduction for LC refining processes varied and was similar or lower than HC refining. **C:** Chip pretreatment with sulphite reduced the shive content. **D:** The lowest shive contents were attained with the S:HT:DD-LC-LC process and the single-stage DD refiner in Kvarnsveden (DDc K 15 t/h).

The SD-LC-F process rendered a shive content that was five times higher than the SD News final pulp and is therefore not interesting for printing paper production. On the other hand, the DD-LC-F process resulted in a shive content close to the SD News pulp. The shive reduction was relatively low over the LC-F system, though, which probably was due to a low shive reduction across the single-stage TF72 LC refiner. Two-stage LC refining in the RTS-SD-LC-LC configuration and the S:HT:DD-LC-LC configuration resulted in larger shive reduction than single-stage LC refining, Figure 45 D.

Chip pretreatment with sulphite (CPT:S-DDu) resulted in somewhat lower shive content than refining with unidirectional segments and no chip pretreatment (DDu), Figure 45C. The CPT:S-DDu-LC process, Figure 45 D, rendered pulps with relatively high shive content which was due to problems with the rotor sealings and the segment design in that trial. In the CPT:S-DDu trial, a different feeding segment design was used, and the resulting pulps had lower shive content, similar to the SD News pulp. The lowest shive content, 52 shives/g (PulpEye), was attained with the S:HT:DDc-LC-LC process, and it was close to the final pulps for the production of magazine grades in Braviken (not shown in Figures 45).

Addition of sodium sulphite to the RTS main line reduced the shive content by over 50% and thereby the level of the SD News pulp was reached. Combinations of high intensity refining, sodium sulphite addition and high temperature seems to be beneficial for low shive content, which has also been shown by Vesterlind and Höglund (2006), Johansson *et al.* (2011) and Nelsson *et al.* (2017).

8.4.2 In-plane strength

A sufficiently high tensile index and strain at break are important for paper runnability in printing presses, section 3.3, but for highly calendered papers, especially those with low basis weight printed by the rotogravure process, a low shive content is also important (Holmen Paper experience, see also *e.g.*, Höglund *et al.* 1976, Fjerdingen *et al.* 1997, Gregersen *et al.* 2000).

As shown in section 8.3, it is possible to reach a tensile index level, that is similar to the single disc based final pulp (SD News), with simplified processes at a low SRE. Also, tensile energy absorption (TEA) and strain at break are similar for the S:HT:DDc-LC-LC pulp and the SD-SD-LC-LC+SD final pulp, Table A3, Appendix 2.

For papers printed by the rotogravure process, there is often a limit in tear strength of the paper (Holmen Paper experience), below which the paper runnability on the paper machine (CD tear decisive) and in printing presses (MD tear decisive) can be affected. However, in most cases, the relatively low tear index (around 6.5-7 Nm^2/kg) of the short fibred DD pulps has not been an issue.

Thus, for simplified processes, it is likely most important to optimize tensile index, strain at break and shive content. Starts and stops of refiners tend to produce large quantities of shives which can cause problems, even for a pulp produced with a normal screening system. This issue must be considered for simplified processes, which is discussed in chapter 9.

8.4.3 Light scattering

The studied main line HC and HC-LC process configurations yielded pulps with a large variation in light scattering coefficient at a given tensile index, Figures 46 A-D. DD refiners operating at normal conditions produced pulps with around 5 m^2/kg higher light scattering coefficient at a given tensile index than the SD refiners, whereas the high speed RTS and CD refiners produced pulps with only marginally higher light scattering than the SD refiners, Figure 46 A.

The light scattering coefficient did not increase significantly over the LC refiners which seems to be an effect of less external fibrillation and peeling of the fibre walls and therefore less fines creation, Figure 46 B, see Paper V for more details. The relatively large increase in light scattering over the LC-F system for the SD-LC-F trial is a probably a combined effect of 0.2 mm reduction of the fibre length, Figure 50, and a larger share of fines since the screen accepts sample was taken at low consistency and in the DD-LC-F trial, the pulp was sampled after dewatering on disc filters.

Unidirectional segments resulted in 1-2 m^2/kg higher light scattering coefficient at a given tensile index whereas chip pretreatment with the Impressafiner yielded pulp with lower light scattering, especially when sodium sulphite was added, Figure 46 C.

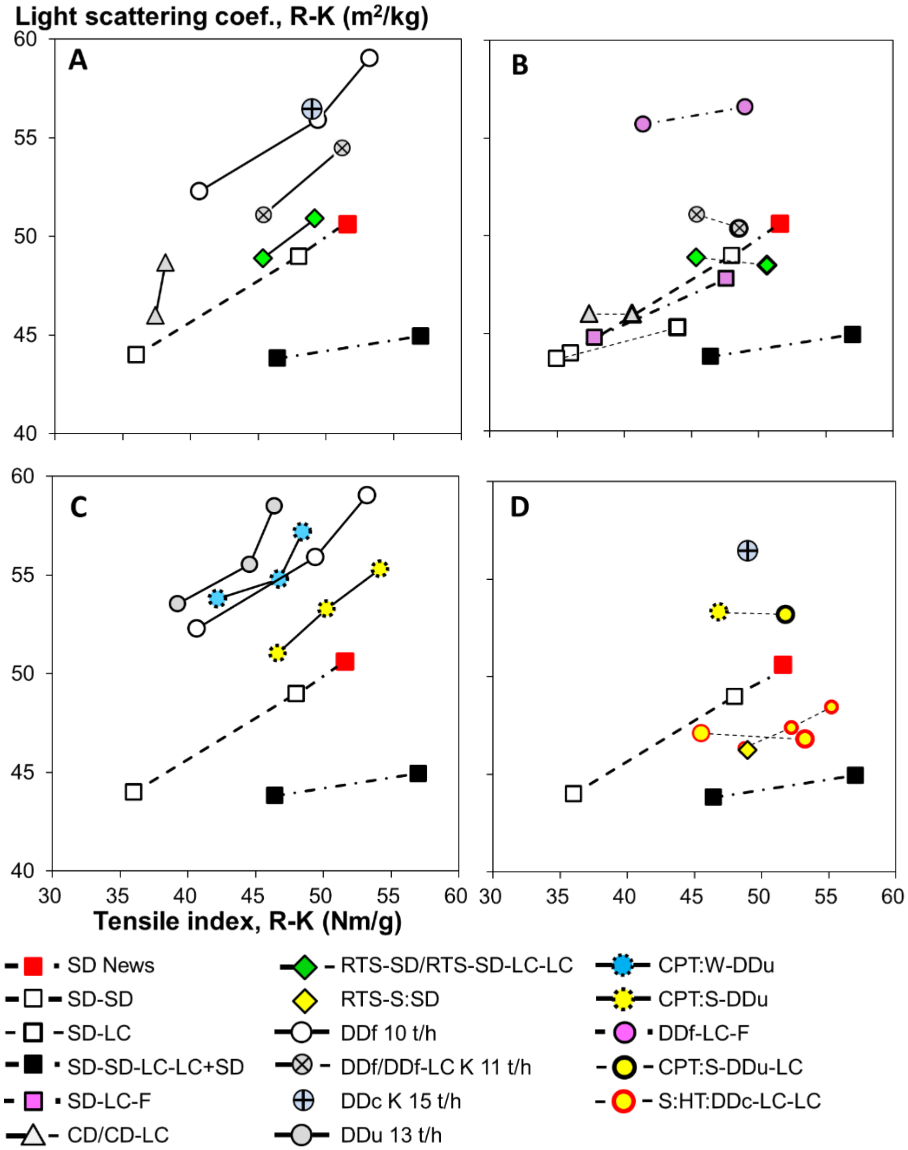

Figure 46. A: DD refining under normal conditions produces pulps with the highest light scattering coefficient at a given tensile index. **B:** For the processes incorporating LC refining there was no or only a slight increase in the light scattering coefficient. **C:** Unidirectional segments resulted in increased light scattering coefficient whereas chip pretreatment with the Impressafiner reduced it. **D:** All treatments with sulphite resulted in lower light scattering.

The light scattering coefficients of Rapid-Köthen handsheets for the S:HT:DDc-LC-LC and the SD-SD-LC-LC+SD processes, Figure 46 D, were around 5 m^2/kg lower than similar pulps from earlier studies. This is probably caused by some anomality in the lab procedure at the time. In Figure 47, the light scattering coefficient of ISO handsheets is shown and in this case the level of light scattering is normal. However, measurements on sheets formed in both ways, show that the light scattering coefficient is somewhat higher for the S:HT:DDc-LC-LC process than the SD-SD-LC-LC+SD reference.

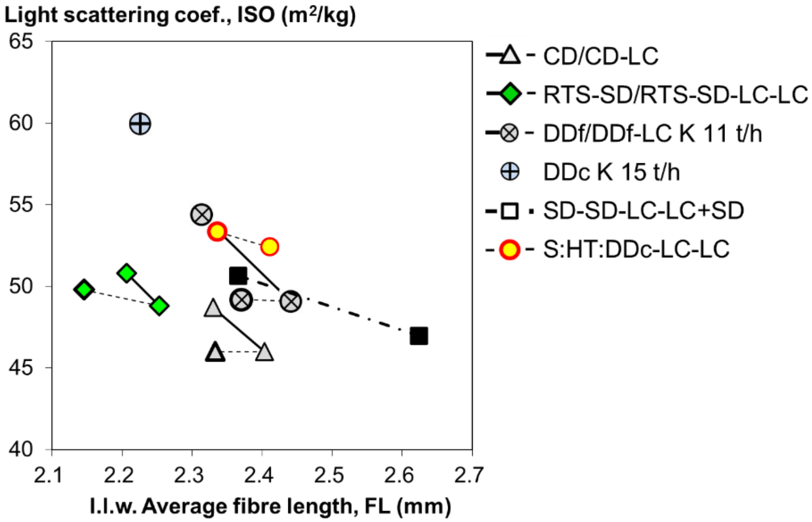

Figure 47. The DD and SD refiners rendered pulps with higher light scattering coefficient at given length-length-weighted average fibre length (FiberLab) than the high-speed RTS and CD refiners. Data from Paper V.

Interestingly, DD refiners produce pulps with higher light scattering coefficient at a given fibre length compared to the high-speed CD and SD (RTS) refiners, Figure 47. This contradicts conclusions of Sundström *et al.* (1993) and also of McDonald *et al.* (2004) who state, *"It is evident that the scattering coefficient is a well-defined function of the fibre length, expressed as the 'L' factor of the pulp and is completely independent of the process used to make it."* **This is obviously not true for all processes**, as indicated by the present results as well as results presented by Hill *et al.* (2017). The difference in fines content Table A1 and A2 Appendix 2, only partly contribute to the relatively large difference between DD and RTS refining. The higher light scattering of the fibre fraction (BMcN >50) for the DD pulp can be one factor, Figure 48. The only fibre property, measured in the present investigations, that might contribute to the higher light scattering of the fibre fraction, is the lower fibre wall thickness of the DD pulps, Figure 51. Braaten (2000) also reported higher light scattering coefficient of the fibre fraction for pulps with lower fibre wall thickness. The light scattering data of the fibre fractions are from the study reported in Paper V, however that data was not presented in Paper V but are provided in Table A1, Appendix 2.

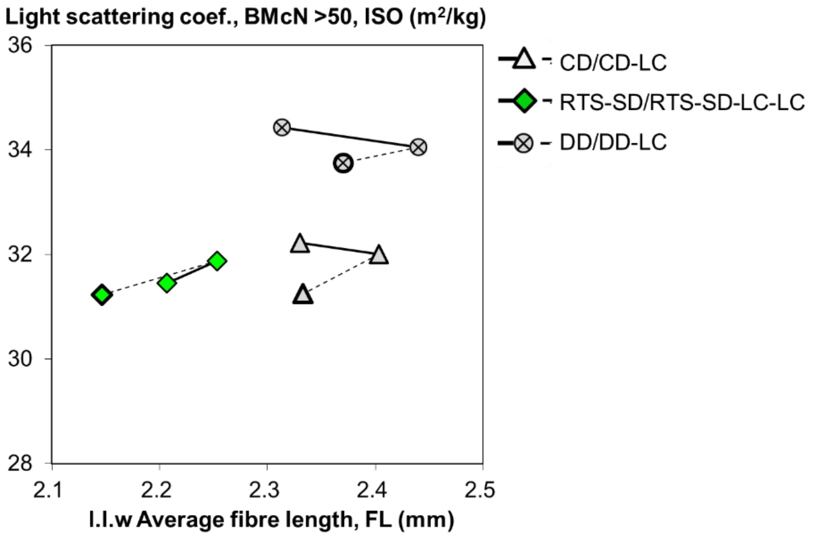

Figure 48. The fibre fraction (BMcN >50) of the DD pulp has higher light scattering coefficient at a given length-length-weighted average fibre length (FiberLab) compared to CD and RTS fibre fractions.

If a bulky pulp with high light scattering is required, normal DD refining without application of sodium sulphite is preferable, moreover, LC refining should be avoided, Figure 49.

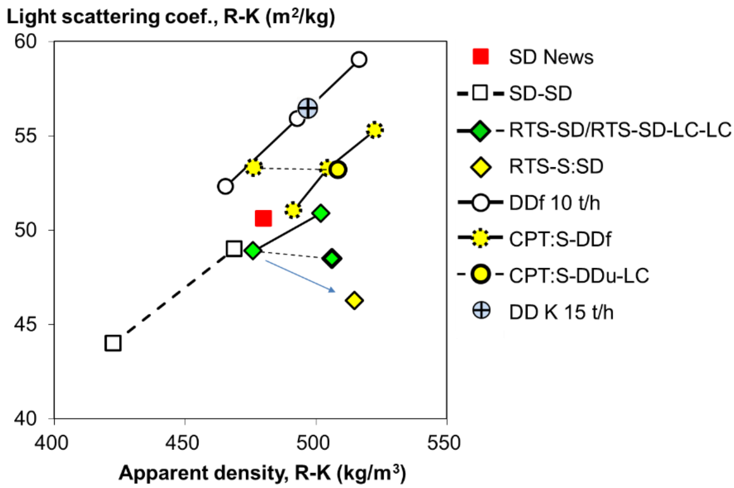

Figure 49. At a given density, the difference in light scattering coefficient between DD and SD refining is smaller than at a given tensile index. Sodium sulphite addition and LC refining both reduce light scattering coefficient at a given density. The blue arrow indicates the change due to sulphite addition at similar SRE for the RTS refining.

8.4.4 Fibre morphology

Fibre length

As seen in Figure 50 A, the DD and high-speed SD refiners (RTS and CD 1800 rpm) produced pulps with around 0.3 mm lower length-weighted average fibre length at a given tensile index compared to the SD refiners operating at 1500 rpm, which is normal. DD refining with unidirectional segments yielded pulp with lower fibre length at given tensile index than refining with fine bidirectional segments, Figure 50 C.

The fibre length reduction over the LC refiners varied from no reduction to a larger reduction than HC refining. The LC-F processes reduced the fibre length relatively much, Figure 50 B. The two-stage LC refining in the S:HT:DDc-LC-LC trial resulted in a relatively large tensile index increase, 8 Nm/g, with only 0.06 mm reduction in average fibre length. The LC refining of the RTS pulp was also made in two-stages, with the same type of refiners and similar production rate, but in this case, the fibre length reduction was larger compared at a given increase in tensile index even though the refiner loads were lower. Whether this is because RTS pulp is more sensitive to LC refining than DD pulp or whether it is an effect of the sodium sulphite addition to the DD refining, is not clear.

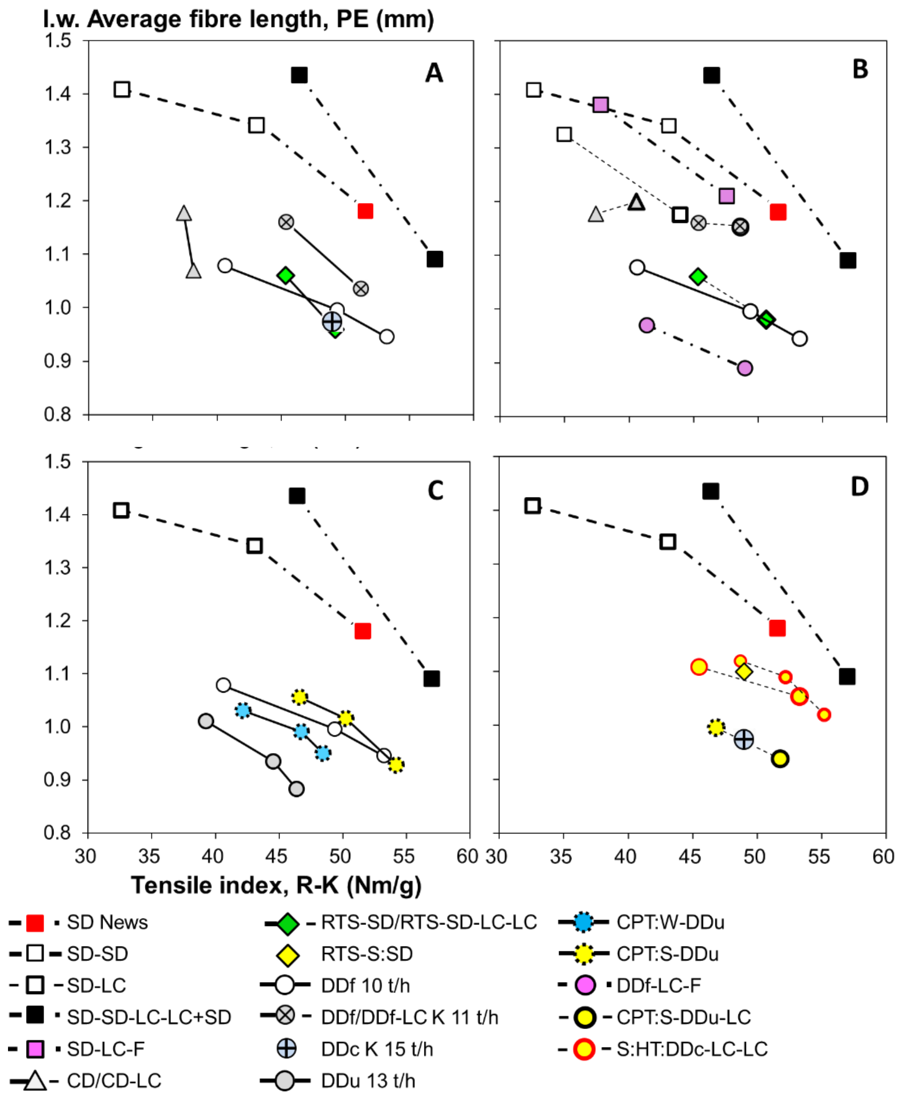

Figure 50. A: The high intensity refiners (DD, RTS, CD 1800) produced pulps with lower fibre length than the SD refiners. **B:** The LC refiners showed a large variation in fibre length reduction. **C:** Mechanical chip pretreatment with the Impressafiner before DD refining (CPT:W-DDu) resulted in higher fibre length at a given tensile index. Adding sodium sulphite after the Impressafiner increased the tensile index and thereby improved the fibre length - tensile index relationship. **D:** The S:HT:DD-LC-LC and RTS-S:SD processes yielded pulps with relatively high fibre length.

Mechanical chip pretreatment with the Impressafiner before DD refining resulted in higher fibre length at a given tensile index, Figure 50 C. The Impressafiner treatment opens up the chip structure (Nelsson *et al.* 2012) which seems to make the fibres more resilient to the relatively harsh conditions prevailing in the DD refiner equipped with feeding segments. Thus, the combination of Impressafiner pretreatment and DD refining with feeding segments yielded pulp with similar fibre length as DD refining with fine bidirectional segments. Adding sodium sulphite after the Impressafiner increased the tensile index and thereby the fibre length – tensile index relationship was shifted even further.

The S:HT:DD-LC-LC and RTS-S:SD processes yielded pulps with only 0.1 mm lower fibre lengths at a given tensile index compared to the SD News, Figure 50 D.

Fibre wall properties

The importance of conformability and bonding ability of the fibre fraction was emphasised in section 2.3.2 and chapter 3. External fibrillation and fibre wall thickness, which are both important for tensile strength development (*e.g.*, Lammi and Heikkurinen 1997, Kang *et al.* 2006, Reyier-Österling 2012), are shown in Figure 51 for some of the studied processes.

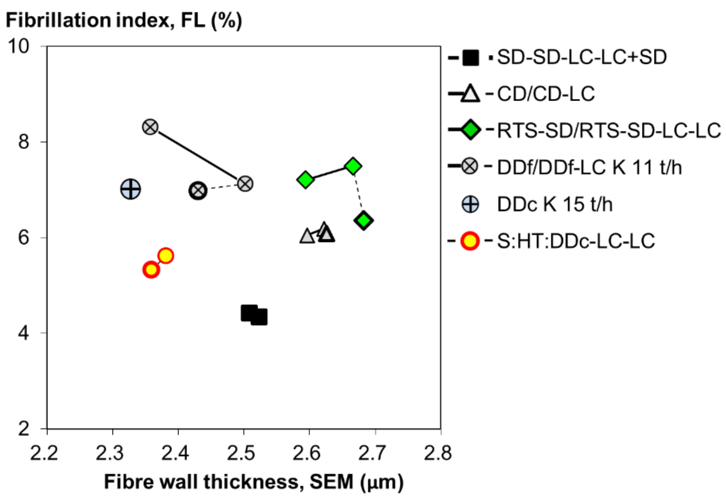

Figure 51. The high intensity refiners (DD, RTS, CD 1800 rpm) produced pulps with a higher degree of fibrillation, measured with FiberLab (FL), compared to SD refining and the DD refiners produced pulps with low fibre wall thickness as well.

The high intensity refiners produce pulps with higher fibrillation than the two-stage SD refiners and the DD refiners yielded the lowest fibre wall thickness. However, the pulp from the S:HT:DDc refining operating under relatively extreme conditions, with sodium sulphite addition and high housing pressure, had lower fibrillation than the "normal" DD refining. The LC refiners and the rejects system in the SD-SD-LC-LC+SD process did not affect either fibrillation or fibre wall thickness, whereas increased SRE in the Kvarnsveden DD refiner increased fibrillation and decreased fibre wall thickness.

The proportion of split fibres was considerably higher for DD refining, 36%, and RTS refining, 31% than for SD refining, 19%, Table A1, Appendix 2. This is in agreement with earlier comparisons between SD refiners and high intensity refiners (Kure *et al.* 2000, Pöhler and Heikkurinen 2003).

Fibre bonding

The bonding ability of the fibres was also evaluated by means of density and Z-strength of the BMcN >50 fibre fraction for three configurations, Figure 52. The DD pulp in the S:HT:DDc-LC-LC process had higher Z-strength at a given density than the SD pulp although the specific refining energy was 440 kWh/adt lower.

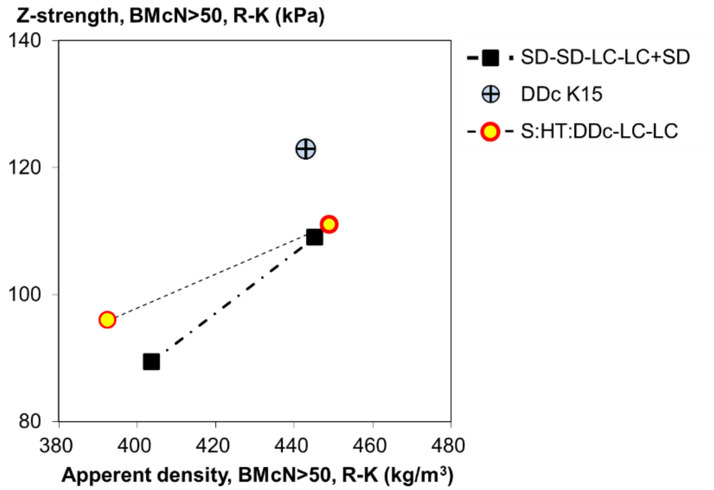

Figure 52. DD refining produced fibres (BMcN >50) with higher Z-strength at a given density than SD refining. Fibres with high bonding can be produced without separate treatment of long fibres in a rejects refining system.

However, the development of the Z-strength was lower for the two-stage LC refining than over the rejects system in the SD line and thereby the Z-strength of the final pulps from the two processes ended up at the same level. DD refining under normal conditions rendered the highest Z-strength and this parameter is particularly important for papers printed by the offset process where viscous and tacky inks are used.

Fibre curl

The DD-refiners produced pulps with the highest fibre curl at a given tensile index and the SD refiners the lowest, Figure 53. Curl was reduced over all LC refiners, whereas it increased for the DD and RTS refiners when the SRE was increased, which agrees well with the study by Ferritsius *et al.* (2012). For the SD-SD-LC-LC+SD process, with screening and rejects refining, fibre curl was unchanged, even though the process included third stage LC refining. The HC rejects refining most likely re-introduced curl into the fibres.

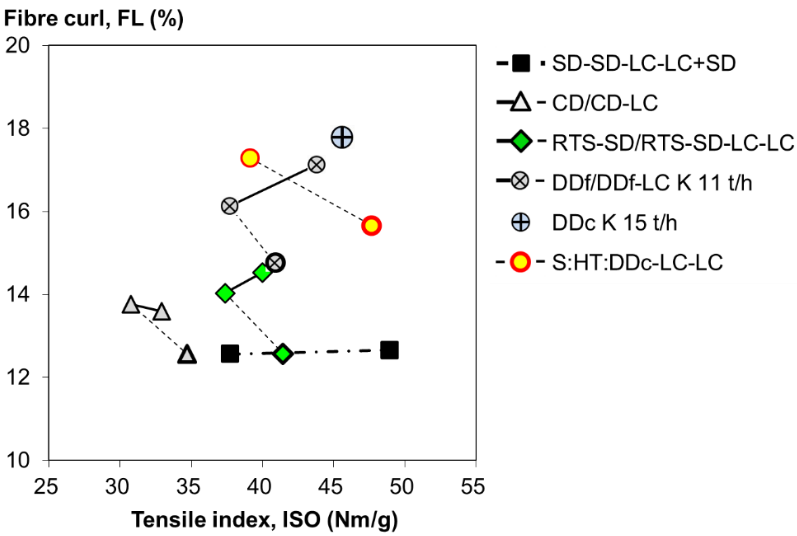

Figure 53. Fibre curl (FiberLab) was reduced across all LC refiners, whereas it increased with tensile index (increased specific refining energy) for the RTS and DD refiners.

8.4.5 Pulp quality evaluation methods affect conclusions

In Figure 54, tensile index and average fibre length are presented in two ways: length-length-weighted average fibre length versus ISO tensile index (left) and length-weighted average fibre length versus R-K tensile index (right).

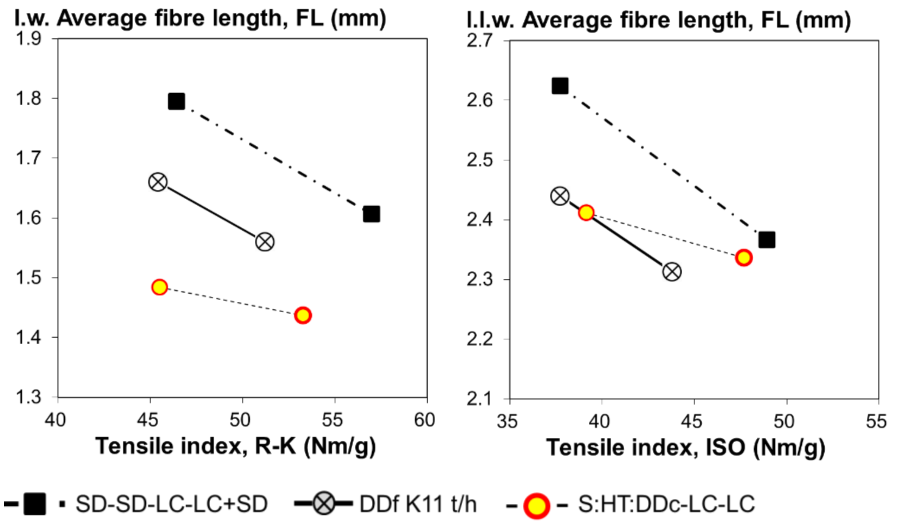

Figure 54. Length-length-weighted average fibre length (FiberLab) versus ISO tensile index (**left**) and length-weighted average fibre length (Fiberlab) versus R-K tensile index (**right**) for the pulps investigated in Paper VI and the DD pulp from Paper V. These two ways of characterizing the same pulps result in different ranking of the processes.

The two alternatives used to compare pulp characteristics render different conclusions. When length-weighted average fibre length is plotted versus Rapid-Köthen tensile index, the impression is that it is a rather large difference between the processes, with the SD final pulp exhibiting "higher quality" than the S:HT:DDc-LC-LC pulp. Moreover, the DD refiner in Kvarnsveden yields pulp with considerably higher fibre length than the DD refiner in the S:HT:DDc-LC-LC process. On the other hand, if length-length-weighted average fibre length is plotted versus ISO tensile index, the SD final pulp and the S:HT:DDc-LC-LC pulp are similar. Also, the two DD refiners produce pulps with similar fibre lengths. According to Ferritsius *et al.* (2018), the length-length-weighted average provides a better representation of the long fibre content in the pulp.

8.4.6 Pulp quality summary

The high intensity refiners (DD and RTS) are more suitable in simplified processes for production of printing papers than SD and CD refiners since they produce pulps with much lower shive content and a higher proportion of fibres with axial splits at a low SRE. Moreover, high intensity refining (DD, RTS) yielded fibres with higher degree of external fibrillation than SD refining.

DD refining resulted in fibres with lower cell wall thickness than SD, RTS and CD (1800 rpm) refining. These fibre properties likely contributed to the higher bonding potential (indicated by Z-strength of fibre fraction handsheets) for fibres produced with DD refining compared to those produced with SD refining, even though the SRE was lower for the DD refining. High speed CD (1800 rpm) and SD (RTS, 2300 rpm) refining rendered pulps with lower light scattering coefficient at a given average fibre length compared to 1500 rpm SD and DD refining.

Fibre and whole pulp properties, similar to a process with rejects (long fibre) treatment, were attained with only main line refining. Four main line configurations produced pulp with low shive content at a tensile index level close to final pulp for newsprints (SD-refiners) at a low specific energy demand. These main line processes could be suitable for simplified processes and are summarized in Table 3. There is a large variation in light scattering coefficient for these configurations which to some extent is related to the fibre length.

Fibres are developed differently in LC refining compared to HC refining. Fibres are not peeled to the same extent in LC refining and thereby less fines are created, which results in a different pulp property profile and limits the use for printing paper applications, see also section 8.5 below. The shive reduction at a given tensile index increase seems to be larger for two-stage than for single-stage LC refining.

Table 3. Four processes that have a shive content close to final pulp for newsprint and low specific energy demand. The SRE and pulp properties are given at a tensile index of 49 Nm/g (R-K handsheets)

Process	SRE (kWh/adt)	Fibre length* (mm)	Light scat. coef. (m^2/kg)
Single-stage DD	1480	0.98	56
CPT:S-DD	1470	1.03	52
S:HT:DD-LC-LC	1200-1300	1.10	50
RTS-S:SD	1540	1.10	46

* Length-weighted average, PulpEye

8.5 LC refining

LC refining has been used rather extensively to reduce the specific energy in mechanical pulp production. However, work by Sandberg *et al.* (2009) and Ferritsius *et al.* (2012) indicate that fibres develop differently in LC refining and HC refining. The study by Ferritsius *et al.* (2012) and the work presented in Paper V, show that the increase in tensile index for HC and LC refining originates from different changes in fibre properties. HC refining reduces fibre wall thickness by peeling which increases the external fibrillation and the amount of fines. This effect is smaller for LC refining, but fibre curl, Figure 53, is reduced which probably contributes to the increase in tensile index for LC refining. Data from the studies reported in Papers V and VI are summarized in Appendix 2. The low increase in light scattering and fibre bonding (Z-strength) across the LC refiners, Figures 46 and 52, could be an effect of the lower degree of fibre peeling in LC refining than in HC refining, Figure 55.

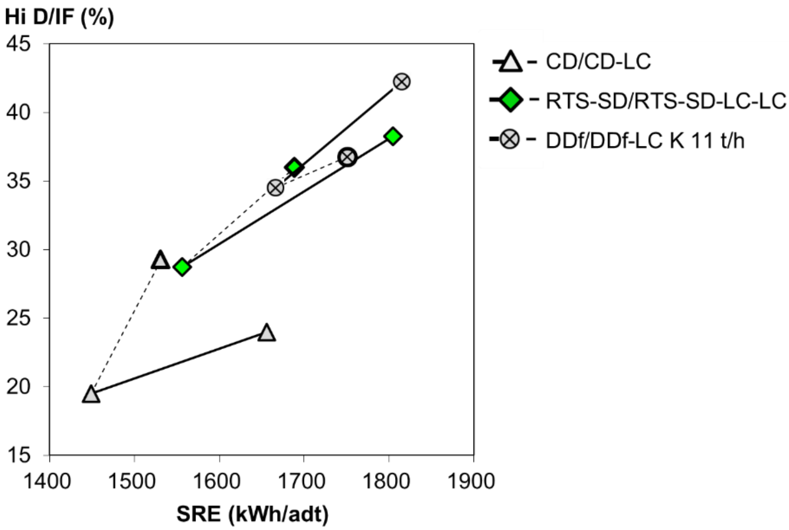

Figure 55. The share of fibres with high degree of fibre wall delamination/internal fibrillation, Hi D/IF, (indicated by Simons' stain) developed similarly for LC refining and high intensity HC refining (DD, RTS). For the CD pulp, the increase in internal fibrillation was larger for LC- than HC refining.

The study by Fernando *et al.* (2013) indicates that the increase in delamination/internal fibrillation (D/IF) of fibre walls (indicated by Simons' stain measurement) is larger for LC refining than HC refining. The same method was used in this work which, on average, showed a similar increase in the share of fibres with high D/IF for a given SRE applied in LC refining. However, in the present study, both DD and RTS refining increased the D/IF at the same rate as LC refining, but the increase for CD refining was lower and similar to the HC refining reported by Fernando *et al.* (2013). High increase in DI/F for DD refining, similar to the present study, was also reported by Fernando *et al.* 2011. Thus, the conclusion is that high intensity HC refining and LC refining results in similar development of internal fibrillation which is higher than SD and CD refining.

In conclusion, the increase in tensile index for LC refining seems to be caused mainly by increases in internal fibrillation and straightening (reduced curl) of the fibres since no other changes were observed in the measured fibre properties.

Sandberg *et al.* (2021) presented data from the same RTS line in Hallsta that was studied in the present work (Paper V). They showed that in a two-stage LC refiner configuration, the efficiency η (as defined in section 6.2) is higher for the first stage refiner than for the second stage refiner, Figure 56. This might be an effect of larger reduction of fibre curl in the first LC refiner (not measured).

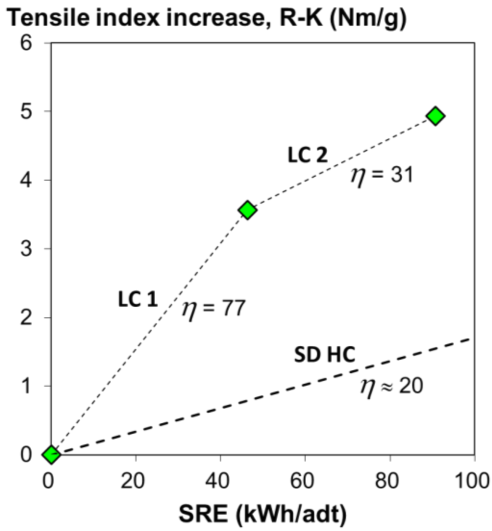

Figure 56. The efficiency η (section 6.2) is much lower for the second LC refining stage in the two-stage main line LC refining in the Hallsta mill, Figure 29. The thick dashed line represents an average curve for second stage SD HC refiners. LC refiner data from Sandberg *et al.* (2021).

Since the increase in fibre bonding (indicated by fibre fraction Z-strength and external fibrillation) for LC refining was lower than for HC refining, it is preferable to combine LC refining with HC refining that yields fibres with a high degree of fibre development, like DD refining. The reasons for the different fibre development in HC and LC refining have not been investigated in this work, but two important differences that might have an effect are the refiner bar crossing velocity and refining temperature, that are much higher in HC refining.

Low consistency refining as a second stage after primary HC refining, is mainly interesting for processes where the production rate over the primary refiners can be increased or where SD HC refiners after primary refining can be replaced. Depending on the primary HC refiner type, the overall production rate can be increased by 20-30% by addition of an LC refining stage in an existing TMP line. This is based on LC refiner data from Hallsta and Braviken, at around 130 kWh/adt applied SRE in the LC refiners.

One drawback with LC refining is that the applied electrical energy is not transformed into steam but into heat resulting in increased pulp temperature. Depending on the overall energy balance in a mill, this may have an impact that needs to be taken into consideration.

8.6 DD refiner installation in Braviken

In 2008, Holmen installed three new RGP68DD refiners in Braviken of which two replaced an old RLP58 line with a configuration similar to the one shown in Figure 27 (top), except that the line contained two-stage HC refining on rejects. The two DD refiners replaced the seven main-line refiners, but the rejects system remained the same. The old TMP line was using around 2500 kWh/adt refining energy to a freeness level of 60 ml and a tensile index of 55 Nm/g (R-K). The TMP line supplied PM51 which produced high quality low basis weight directory papers. The fibre furnish to PM51 consisted of around 75% TMP, 20-25% deinked pulp (DIP) and 0-5% chemical pulp. The paper contained 5-10% filler, consisting of a mix of GCC and calcined clay.

With the DD pulp, the target freeness had to be raised to 70 ml to manage dewatering in the wire section of the paper machine and with that, the tensile index (measured on handsheets) was reduced to around 50 Nm/g. The light scattering coefficient was 5 m^2/kg higher for the DD pulp and the specific refining energy was 600 kWh/adt lower. Moreover, the pulp had 20% lower length-weighted average fibre length and around 15% lower tear index. Overall, many people would consider the new DD pulp as being of considerably poorer quality, as judged from the lab measurements. However, the paper runnability on the PM and in the printing presses was as good as with the SD pulp, and moreover, the paper quality was improved. In Table 4, average properties (around 100 measurements) of one of the main products on PM51, 36 g/m^2 directory paper, are shown for two months before and after the installation of DD refiners in Braviken. The average use of reinforcement kraft pulp was reduced by 60% and due to the higher light scattering coefficient of the DD pulp, the amount of calcined clay filler could be reduced by 90% and replaced with lower cost GCC. Most of the time, 36 g/m^2 directory paper could be produced with no kraft pulp and no calcined clay filler.

Table 4. Pulp and paper properties before and after change of refiners. Two months averages (around 200 measurements). Paper data is for 36 g/m^2 directory paper.

Pulp properties		SD	DD
Specific refining energy	kWh/adt	2500	1900
Light scattering coefficient, 550 nm	m^2/kg	52	57
Tensile index (Rapid-Köthen)	Nm/g	55	50
Fibre length l.w.a.[a], PulpEye	mm	1.25	1.02
Paper properties			
Light scattering coefficient	m^2/kg	53.5	53.5
Tensile index MD	Nm/g	65.4	68.6
Tear strength CD	mN	253	261
Anisotropy[b]		3.67	3.66
Surface roughness, top side	ml/min	27.7	28.3
Surface roughness, bottom side	ml/min	28.3	31.5
Chemical pulp ratio[c]	%	2.77	1.11
Calcinated clay dose[d]	kg/adt	21.2	2.11

[a] l.w.a. = Length-weighted average
[b] Based on MD/CD tensile index ratio
[c] Based on fibre furnish
[d] Based on whole furnish

Thus, the large focus on maximized fibre length in the mechanical pulping community can be questioned. There are, based on our experiences, obviously other fibre properties that can compensate for a low fibre length. So far, we do not have a clear answer to this, but the high degree of fibrillation and low wall thickness of the DD fibres might be important factors. Also, the paper formation (Ambertec) improved from 2.48 to 2.31, which might be an effect of the lower average fibre length of the DD pulp and the lower amount of chemical pulp.

8.7 Paper machine trials with simplified pulp production processes

Two simplified processes were evaluated on the paper machines in Braviken: DDf-LC-F on PM53 and CTP:S-DDu-LC on PM52. In both trials, the paper machines were producing newsprint that was delivered to regular customers. The printing performance was evaluated in two of the printing houses.

8.7.1 DD-refining combined with LC refining and screening

The simplified process, denoted DDf-LC-F, without HC rejects refining and where the screen rejects are returned to the LC refiner feed is described in section 7.5.1 and Paper III. Paper machine data from this trial have not been published before. However, for this work it was considered to be of interest to also include the PM data. The trial was performed during production of 42 g/m^2 standard newsprint on PM53. At the time of the trial, PM53 was fed with a pulp mix of 30% SD TMP and 15% DD TMP as well as 55% DIP. During the trial, the TMP proportion was increased from the reference level of 45% to 77% and no SD pulp was supplied. To maintain the ash content constant at 9%, the amount of fresh GCC was increased from 4.7 to 7.9%. Paper data are presented in Table 5.

Table 5. Paper quality data for the reference and the DD-LC-F trial.

Paper property		Ref.	DDf-LC-F
Tensile index MD	Nm/g	61	59
Tensile index CD	Nm/g	16	17
TEA	J/g	15	14
Tear strength	mN	320	270
Light scattering coef.	m^2/kg	55	58
Roughness	ml/min	34	35
Ash content	%	9.0	9.0

The geometrical mean tensile index was similar for the reference and trial paper, but tear strength was reduced by 13% and the light scattering coefficient increased by 5% with the DDf-LC-F pulp. These differences might be a combined effect of the increased share of short-fibred DD TMP and the reduced DIP share that contained around 30% chemical pulp fibres. No web-breaks occurred on the PM during the 6 hours trial nor when the paper was printed.

8.7.2 Chip pretreatment before DD refining and LC refining

At a later stage, a process with a lower number of unit operations was evaluated on PM52. At the time, PM53 had started to produce magazine grades and PM52 was still mainly producing newsprint. The process, denoted CPT:S-DDu-LC, which is described in more detail in section 7.5.2 and in Paper IV, consisted of chip pretreatment with sulphite, DD refining with unidirectional segments and single-stage LC refining.

During the entire trial as well as during the reference period, PM52 was producing 42 g/m^2 standard newsprint. Unfortunately, the paper machine speed had to be reduced from 1621 m/min during the reference run down to 1425 m/min for the CPT:S-DDu-LC trial. This was due to initial problems in the TMP plant when trying to operate the refiners at high pressure which caused an initial shortage of pulp. The reduced speed might have resulted in somewhat higher strength properties than the normal speed. After some initial problems, the PM was operating under stable conditions with 100% CPT:S-DDu-LC pulp for four hours. Paper samples were taken during a period of 90 minutes, starting four hours after the furnish change to the trial pulp. There were no web breaks during the CPT:S-DDu-LC trial or during the reference trial. In Table 6, paper properties are shown for the CPT:S-DDu-LC paper and the reference. The values are averages from three reels of paper. Even though the freeness was higher for the CPT:S-DDu-LC pulp, the air permeability and surface roughness were lower. All properties were equal or somewhat better for the CPT:S-DDu-LC, with the exception of the tear index which was 21% lower.

Paper from the reference and CPT:S-DDu-LC trial was printed in coldset offset in two printing houses (Pressgrannar and V-TAB). The paper was evaluated with respect to set-off, print through, miss-register, linting, etc. The CPT:S-DDu-LC paper had equal or somewhat better printing properties compared to the reference.

Table 6. Properties of final pulps and paper for the CPT:S-DDu-LC trial and the reference (averages of measurements on three reels).

Pulp properties		**Reference**	**CPT:S-DDu-LC**
SRE	kWh/adt	2 160	1 390
CSF	ml	90	109
Tensile index (RK)	Nm/g	53	52
Apparent density (RK)	kg/m^3	504	508
l.w.a. fibre length	mm	1.12	0.94
Light scattering coef.	m^2/kg	50	53
Shive content (PE)	№/g	277	384
Paper properties		**Reference**	**CPT:S-DDu-LC**
Air permeance	ml/min	253±15	215±15
Density	kg/m^3	618±6	624±14
Tear strength CD	mN	343±3	271±7
TEA MD	J/m^2	18.3±0.1	19.2±0.1
Elongation MD	mm	1.02±0.01	1.06±0.01
Tensile strength MD	kN/m	2.94±0.02	2.94±0.03
Anisotropy*		3.65±0.04	3.52±0.04
Light scat. coef.	m^2/kg	54.1±0.9	56.0±0.1
Opacity	%	94.5±0.1	94.6±0
Roughness 1kg, b. s.**	ml/min	109±3	89±4
Roughness 1kg, t. s.**	ml/min	129±3	115±6

* Based on MD/CD tensile index ratio
** b.s. and t.s. are bottom and top side respectively.

9 Concluding remarks

The goals of this work were to increase the understanding of how unit operations can be combined, to provide process configurations with as few unit processes as possible, low specific energy demand and adequate pulp quality for newsprint quality grades. While these goals have clearly been attained, there are some issues that can be discussed further.

Process configurations. The pulp quality – specific energy relationship for a given refiner configuration, can vary considerably depending on wood raw material quality, segment designs and operating conditions mentioned in section 2.3.5. It has not been possible to study the effects of all of these variables in detail in this work. Therefore, it might be possible to improve the performance of any of the studied process concepts. However, at the time of each trial, the operating conditions were considered to be adequate for the quality requirements of the produced paper.

Since this work was performed over a relatively long period, some of the unit operations improved during this time, especially the DD refiner performance. Therefore, it is not straight forward to conclude what is the "best" process configuration. However, it is clear that single-stage HC refining with the RGP68DD refiner has a large potential when it is operated at high production rate. This refiner can be combined with LC refining, which contributes to increased production rate and thereby to an overall increase in energy efficiency. Another interesting combination is the Impressafiner pretreatment of the chips before DD refining, which enabled the DD refiner to be operated at higher intensity (feeding segments and increased production rate) at maintained fibre length.

Of course, there can be other processes that might be suitable for simplified processes in addition to those studied in this work. One such process could be single-stage RTS refining with some form of chip pretreatment, such as Impressafiner or Fiberizer.

It is quite amazing that such a good fibre development and high efficiency can be attained with nothing more than a single-stage RGP68DD refiner operating under normal conditions, except for increased production rate (the data from Kvarnsveden, *DDc K 15 t/h* in the graphs). The fibre length was lower than for the S:HT:DDc-LC-LC process, but still somewhat higher than for the two pulps that were evaluated in paper machine and printing trials, section 8.7. The light scattering coefficient for the *DDc K 15 t/h* pulp was 6 m^2/kg higher than that for the S:HT:DDc-LC-LC pulp and 9 m^2/kg higher than that for the

RTS-SD-LC-LC pulp, which means that less filler is required to attain a given level of opacity. Less filler might improve paper runnability and moreover, mineral fillers do not represent a renewable raw material.

Number of unit operations. Clearly, a large amount of equipment can be omitted for processes without rejects treatment systems. On the other hand, some equipment might be added to the main line, so in the end, the saving in investment cost and auxiliary energy depends on the required production rate and pulp quality profile. Therefore, no estimations of the required number of equipment have been made for the process configurations studied in this work.

Shives. Even though the shive content of some of the studied simplified processes was very low, as measured with an optical fibre analyser, a few large shives might slip through the refiners and cause runnability problems on the paper machine or during printing. Therefore, it might be of value to examine the often totally forgotten machine screens at the paper or board machine. Investing some resources in improving the performance of those screens, such as reduced slot width and maybe additional capacity, would be a good combination with a simplified TMP (or CTMP) process. Also, it might be beneficial to design the simplified process with a small pulper, not a large latency chest, immediately after primary HC refining, to be able to divert the pulp from starts and stops, since this pulp normally contains loads of shives that a subsequent LC refiner will have difficulties to handle fully. A small and well agitated pulper also improves the controllability of the refiners (Sund *et al.* 2021).

Fibre length. Generally, the high intensity refiners yielded pulps with lower average fibre length, Figure 50, which sometimes has been pointed out as unavoidable in strivings for large reductions in specific energy demand. The experiences from the Braviken and Hallsta mills is that a fibre length reduction which is of a “cutting” type, impairs runnability of the pulp on a PM. This kind of fibre length reduction can, for example, be attained in LC refining if the disc gap is too narrow, as shown in Figure 57. A clear indication of the “cutting” type of fibre length reduction is that, at a certain point, the tensile index starts to go down resulting in the J-shaped curve in the figure. On the other hand, a similar fibre length reduction attained from a DD HC refiner, shown in the same figure, does not ruin the PM runnability which has been shown with PM trials in this work, section 8.7, and from the change from SD to DD refiners in Braviken, section 8.6. Pilot trials performed by Nurminen (2001) also indicate that high fibre length is not necessary to achieve high strength properties, as long as the fibres are well fibrillated. A length-weighted average fibre length around 1 mm (PulpEye) seems to be sufficient for pulp produced with RGP68DD refiners. Interestingly, as presented in section 8.6, judged from the lab measurements of the DD and SD pulps when Braviken converted their main line refining, the DD pulp would have been considered to exhibit lower quality than the SD pulp. However, the DD pulp performed better both on the paper machine and in the printing presses and required 600 kWh/adt lower specific refining energy. This emphasizes the need for an increased understanding of the effect of basic fibre properties on paper runnability and quality.

The conclusion is that PM runnability is not a matter of fibre length alone.

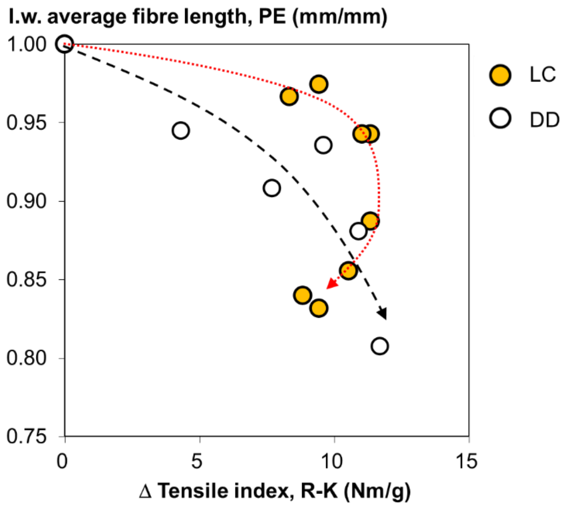

Figure 57. Normalized length-weighted average fibre length for an LC and DD refiner versus tensile index increase over respective refiner type. Too high load (low disc gap) in an LC refiner can cause a “cutting” action resulting in the J-shaped trend.

Mineral fillers. Some of the investigated process configurations rendered pulps with a relatively low light scattering coefficient at a given tensile index, *e.g.*, the RTS-S:SD process, Figure 46. If that pulp would have been LC refined and filler added to it, it would have developed as the blue arrows indicate in Figure 58. Thus, if high strength can be attained with high energy efficiency and the share of filler increased, a lower light scattering of the pulp could be accepted. However, one drawback with this strategy is that the density will increase both by the additional refining and the filler addition. Thus, if a bulky paper is required, it is better to choose a process that produces a pulp with high light scattering at a given density, such as DD refining, Figure 49. On the other hand, many fillers, like GCC, have a lower cost than the pulp which would increase the overall cost efficiency.

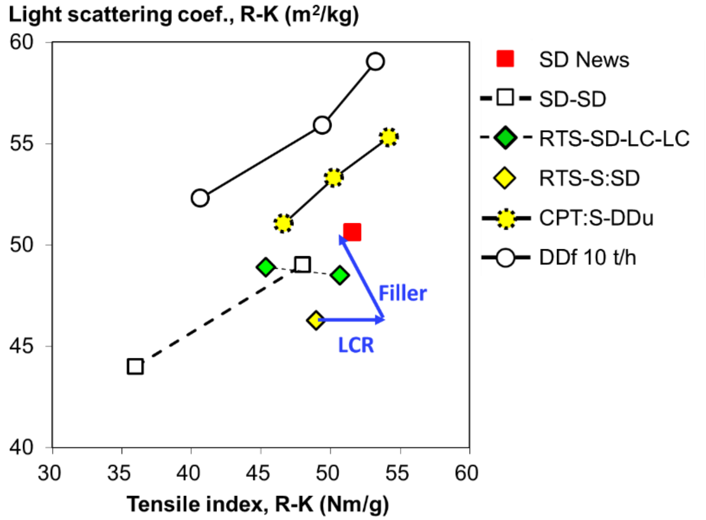

Figure 58. A low light scattering coefficient at a given tensile index can be compensated by additional LC refining and addition of a mineral filler. The arrows in the figure indicate the effects on the light scattering coefficient - tensile index relationship of LC refining and addition of around 3% GCC to the RTS-S:SD pulp.

Old "truths". McDonald *et al.* (2004) stated: "*A common goal of most mechanical pulping studies has been the reduction of specific energy consumption. However, accomplishing this without compromising pulp quality has proven to be elusive*." The work presented in this thesis has clearly shown that it is possible to reduce the specific energy drastically with maintained paper performance while at the same time simplifying the process.

Also, Sundholm (1993) wrote: "*It seems unlikely that anyone will invent an entirely new type of machine which would turn wood into high quality pulp in just one step*" With an RGP68DD refiner this can certainly be achieved today.

Implementation. Unfortunately, it has not been possible to implement a simplified process in any of the Holmen mills, so far. The three DD refiners in the Braviken mill and the two RTS lines in the Hallsta mill are now used for magazine grades, and the simplified processes have not been evaluated for this quality level of TMP, so far. Most likely, it would be possible to implement a similar concept for CTMP lines in integrated board mills, if the shives are handled properly as mentioned above. Whether a similar concept could be used for more demanding raw materials has not been studied, but would be interesting to investigate.

10 Conclusions

The mill-scale studies of simplified process concepts have shown that it is possible to produce mechanical pulp (TMP) for printing paper of newsprint quality, without screening and rejects refining systems, and requiring less than 1500 kWh/adt total specific energy.

Referring to the questions raised in chapter 5, the following conclusions are drawn.

Question 1.
It was necessary to apply high intensity primary stage HC refining (DD or RTS) to reach the target shive content at low specific refining energy. Of the studied refiner types, DD refiners (RGP68DD, 2x1500 rpm) seem to be the most suitable type for simplified processes for printing paper, since they not only produce pulp with low shives content, but also fibres with a high degree of external and internal fibrillation as well as low fibre wall thickness which contribute to high light scattering at a given fibre length.

High production rate and refining temperature (housing pressure) as well as a low charge of sodium sulphite (around 5 kg/adt) reduced the specific refining energy to a given tensile index and contributed to low shive content and high average fibre length at a given tensile index, but resulted in a lower light scattering coefficient than that obtained under normal refining conditions.

Question 2.
LC refining was evaluated both in main line refining and for rejects refining with the main line position showing better results in terms of improved efficiency and loadability. Moreover, since one of the goals of this work was to reduce the process complexity, the main line position is clearly advantageous.

For printing paper applications, the proportion of fibre development in LC refining should preferably be relatively low, since the LC refiners have limited capacity to reduce fibre wall thickness and thereby develop light scattering and fibre fraction Z-strength. It is therefore beneficial to combine LC refining with high intensity HC primary refining, for example DD refining, thereby providing the required level of these quality variables. The main benefit of an LC refining stage after high intensity primary refining is that it enables higher production rate and thereby increased energy efficiency.

Question 3.

Several configurations proved to be suitable for a simplified process without a rejects treatment system. The lowest specific refining energy was attained with the S:HT:DD-LC-LC configuration, which required only 1280 kWh/adt to reach a tensile index of 52 Nm/g (Rapid-Köthen). This is 900 kWh/adt lower SRE than the final pulp for newsprint based on SD HC refining, and over 500 kWh/adt lower than Scandinavian BAT processes (2014). Additionally, the auxiliary specific energy was around 150 kWh/adt lower for processes without a conventional rejects treatment system. At 52 Nm/g tensile index, the light scattering coefficient was 2-3 m^2/kg higher, and length-weighted average fibre length was around 0.1 mm lower for this process than for the SD TMP final pulp. The fibre bonding, indicated by density, tensile index and Z-strength of fibre fraction handsheets, were similar or higher for the S:HT:DD-LC-LC process than the reference SD TMP process with rejects treatment system.

Three additional interesting processes with somewhat lower energy efficiency were:

1. Impressafiner pretreatment of the wood chips with sodium sulphite before DD refining, with or without proceeding LC refining. SRE 1440 kWh/adt to 52 Nm/g tensile index.
2. RTS primary refining with sodium sulphite added before the second stage SD refiner. SRE 1540 kWh/adt to 49 Nm/g tensile index.
3. Single-stage DD refiner operating at relatively high production rate, 15.5 adt/h, and 4 bar housing pressure without sodium sulphite addition. SRE 1480 kWh/adt to 49 Nm/g tensile index

Additional findings from this work

Two simplified processes without rejects systems, DD-LC-F and CPT:S-DD-LC, were evaluated on paper machines and in printing presses. Good runnability was attained both on the paper machines and in the offset printing presses and the paper quality was equivalent to the reference paper except for slightly lower tear index.

High intensity HC refining (DD and RTS) and LC refining results in similar development of internal fibrillation (indicated by Simons' stain measurement) which was higher than CD refining

The energy efficiency was lower for the combination of LC refining and screen fractionation, LC-F process, compared to only LC refining.

Two-stage LC refining had higher shive reduction than single-stage LC refining.

Addition of sodium sulphite after the Impressafiner, or directly to the chips between the plug screw feeder and the refiner, or even to the blow-line between primary and secondary HC refiners resulted in similar effects on shives content and tensile index increase.

Chip pretreatment with the Impressafiner before DD refining resulted in higher fibre length at a given tensile index than DD refining alone, especially for refining with feeding segment design.

For paper qualities where a bulky structure with high opacity (light scattering) is required, single-stage DD refining without either sulphite addition or LC refining is the best choice.

SD and DD refiners produce fines with different fibrillar fines size distributions. The SD process generated more of small fibrillar fines which probably explain the higher tensile index at given apparent density of the SD-News pulp.

For simplified processes, it might be necessary to improve the screening operation at the paper machine or board machine to remove the few larger shives that might pass through the refiners.

Explicit effects on the number of unit operations and production cost have not been evaluated in this work, but clearly both investment and variable costs as well as fixed costs (manning and maintenance) can be reduced with a simplified process. Moreover, the pulp quality from a simplified process will be easier to control.

11 Recommendations for future work

Sundholm (1993) estimated the lowest achievable specific refining energy for newsprint TMP to be between 800 and 1200 kWh/adt. If this would be true, a very high efficiency would have been reached in the present work, since the lowest attained SRE at this quality level was below 1300 kWh/adt. Most likely, the theoretical minimum specific energy is considerably lower than 1200 kWh/adt, which can encourage continued research aimed at further reducing the specific refining energy. More knowledge on the refining mechanics at the fibre level would certainly help to design refining equipment with even higher efficiencies than those studied in this work. Also, a deeper understanding of how fibre properties affect paper machine runnability could provide directions on how to develop fibres at high energy efficiency.

It would also be interesting to apply the approach used in this work for other products such as paperboard and also for other raw materials than spruce.

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Appendix 1

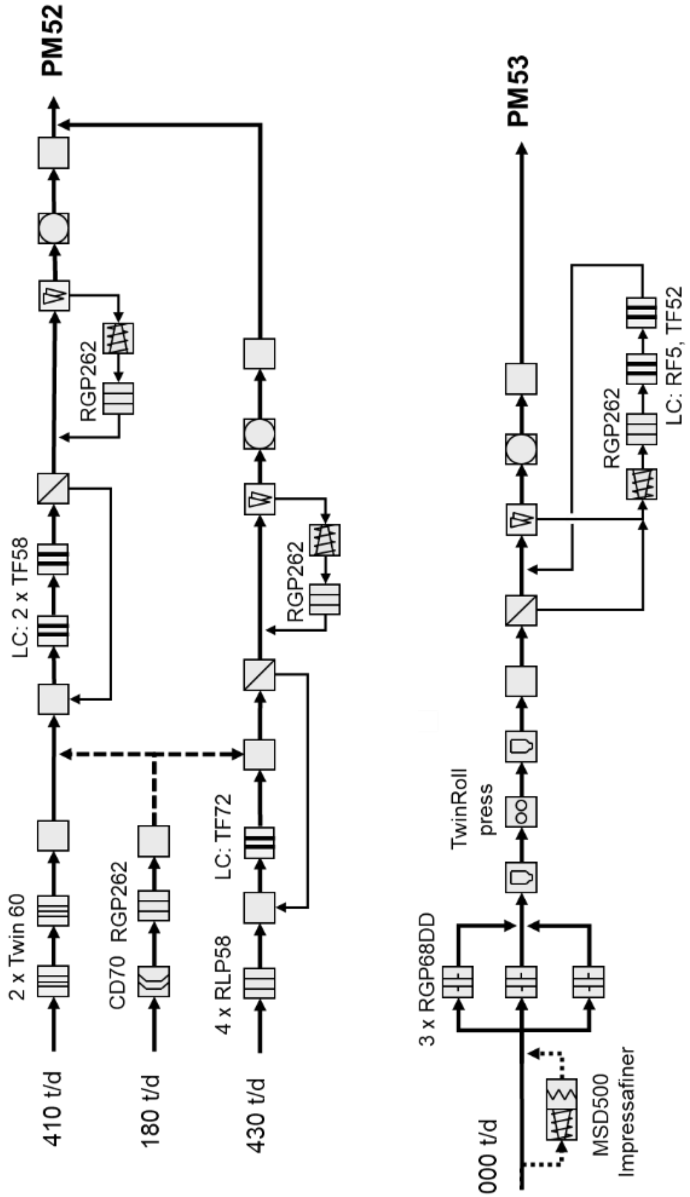

Figure A1. Overview of the TMP mill in Braviken today (2022)

Appendix 2

Tabell A1. Data for HC and HC-LC refining, Paper V

		CD			DD			RTS		
		HC1	**HC2**	**HC1-LC**	**HC1**	**HC2**	**HC1-LC**	**HC1**	**HC2**	**HC1-LC**
SRE	kWh/adt	1449	1656	1531	1666	1815	1751	1556	1805	1689
CSF, ml		212	155	181	194	109	167	132	94	95
Somerville shives	%	1.4	0.9	1.0	0.4	0.2	0.3	0.3	0.2	0.1
BMcNett R16	%	30.7	22.6	30.8	31.3	26.0	30.8	23.7	20.9	18.8
BMcN 16-30	%	23.4	24.9	23.8	22.2	22.7	22.1	24.0	23.7	26.2
BMcN 30-50	%	12.1	14.1	12.5	11.3	11.8	11.1	13.8	14.2	14.8
BMcN 50 100	%	8.5	10.3	9.5	8.3	9.5	8.3	10.6	11.4	11.6
BMcN 100-200	%	4.0	4.5	4.0	4.1	4.6	4.0	4.8	5.0	5.1
BMcN P200	%	21.3	23.5	19.6	22.9	25.5	23.8	23.1	24.9	23.5
ISO Handsheets										
Density	kg/m^3	359	392	377	406	462	421	418	450	439
Tensile index	kNm/kg	30.7	32.9	34.7	37.7	43.8	40.9	37.4	40.0	41.5
Elongation	%	1.75	1.74	1.80	2.05	2.25	2.12	1.99	2.06	1.94
TEA	J/kg	354	382	414	527	679	593	507	566	547
Tear index	Nm^2/kg	7.9	7.4	8.0	8.2	7.6	8.3	7.4	7.3	6.8
Light scat. Coef.	m^2/kg	44.8	47.6	45.2	49.1	54.4	49.2	48.8	50.8	49.8
Rapid-Köthen Handsheets										
Density	kg/m^3	445	458	451	478	509	479	476	502	506
Tensile index	kNm/kg	37.4	38.2	40.0	46.2	51.2	48.6	45.4	49.2	50.7
Elongation	%	1.63	1.66	1.68	1.90	2.16	1.96	1.77	1.86	1.75
Tear index	Nm^2/kg	8.1	7.1	7.6	8.0	7.3	8.0	7.1	6.9	7.0
Light scat. Coef.	m^2/kg	46.0	48.7	46.0	51.1	54.5	50.4	48.9	50.9	48.5
PulpEye										
Fiberlength l.w.	mm	1.18	1.07	1.20	1.16	1.04	1.16	1.03	1.00	0.98
Fibershape	%	5.6	6.1	4.8	6.4	7.1	5.8	5.8	6.1	5.2
Shives	№/g	1045	914	1013	373	182	273	518	309	342
FiberLab										
L(l)	mm	1.64	1.56	1.62	1.66	1.56	1.64	1.49	1.45	1.41
L(l2)	mm	2.40	2.33	2.33	2.44	2.31	2.37	2.25	2.21	2.15
Width (n)	µm	24.9	24.8	24.9	24.8	23.8	21.6	24.2	23.7	23.2
CWT (n)	µm	7.7	7.6	7.8	7.2	6.8	7.3	7.2	7.2	7.2
Curl (n)	%	13.8	13.6	12.6	16.1	17.1	14.8	14.0	14.5	12.6
Fibrillation (n)	%	6.2	6.0	6.1	7.1	8.1	6.8	7.5	7.2	6.4
BMcN>50 ISO Handsheets										
Density	kg/m^3	227	235	241	253	320	275	265	280	282
Tensile index	kNm/kg	6.8	6.7	7.4	12.7	19.1	15.4	11.7	12.8	13.8
Light scat. Coef.	m^2/kg	32.0	32.2	31.3	34.1	34.4	33.8	31.9	31.5	31.2
Simons' stain										
Non D/IF		56.5	47	43.75	38.75	29.25	36.5	41.25	34.25	34
Low D/IF		24	29	27	26.75	28.5	26.75	30	27.5	30
High D/IF		19.5	24	29.25	34.5	42.25	36.75	28.75	38.25	36
FiberLab BMcN>50										
L(l)	mm	2.10	1.99	2.06	2.08	2.00	2.06	1.95	1.93	1.89
L(l2)	mm	2.66	2.51	2.58	2.66	2.61	2.64	2.55	2.52	2.45
Width (n)	µm	30.8	30.5	30.3	30.4	29.0	30.1	29.7	29.3	29.0
CWT (n)	µm	10.9	10.8	10.8	10.3	9.5	10.2	10.3	10.0	10.2
Curl (n)	%	12.1	12.4	11.4	14.6	17.4	14.6	13.6	14.9	13.0
Fibrillation (n)	%	4.0	4.0	4.0	4.8	5.9	5.0	5.2	5.6	5.1

Table A2. Process variables for the two S:HT:DDc-LC-LC trials

	Equipment type	Segments	Production rate	Mass reject rate	Power	SRE	Consistency	Disc gap	Pressure in/out
SD-reference			adt/h	%	MW	kWh/adt	%	mm	MPa
Primary refiner	HC Twin 60		17		18.5	1090	45	0.83/0.81	0.34/0.39
Secondary refiner	HC Twin 60		17		10.1	595	40	0.93/1.19	- /0.35
Tertiary refiners	LC TwiFlo 52	58TC425-426	23		1.6/1.7	70/74	4.4		
Screens	Ahlström F5	0.2 mm slots	23	26			Feed: 2.1		
Hydrocyclones	Noss AM80F		24	29			Feed: 0.7		
Rejects refiner	HC RGP262		7		5.3	312	33		
DD-LC-LC, trial 1									
Primary refiner	RGP68DD	828/847	18.0		21.8	1211	38	0.72	0.67/0.66
Secondary refiner	LC TwiFlo 52	58TC425-426	18.0		1.7/1.8	94/100	5.0		
DD-LC-LC, trial 2									
Primary refiner	RGP68DD	828/847	18.3		22.3	1219	37	0.59	0.65/0.65
Secondary refiner	LC TwiFlo 52	58TC425-426	18.3		1.7/1.6	93/87	4.8		

Table A3. Pulp properties for trial 2 with S:HT:DDc-LC-LC and the reference pulp (Paper VI)

		S:HT:DDc-LC-LC		SD-SD-LC-LC+SD	
		After DD	After LC	Latency	Final
SEC (kWh/adt)	kWh/adt	1246	1430	1685	2192
Braviken					
CSF	ml	172	114	170	81
Apparent density	kg/m^3	494	527	472	529
Tensile index	Nm/g	45.5	53.3	46.4	57.0
Stretch at break	mm	2.03	1.95	1.88	1.96
Light scattering coef.	m^2/kg	47.1	46.8	43.8	45.0
Tear index	Nm^2/kg	7.3	6.7	8.5	7.1
Fibre length lwa*	mm	1.11	1.05	1.44	1.09
Shives sum	№/g	182	83	588	96
Shives >3 mm	№/g	83	18	158	9
Valmet					
Tensile index	Nm/g	43.2	50.8	40.3	52.2
Light scattering coef.	m^2/kg	49	48	44	46
Som. Shives	%	0.29	0.09	0.55	0.04
Fines B	%	37	39.4	41.3	47.4
Kvarnsveden					
Apparent density	kg/m^3	408	452	373	454
Tensile index	Nm/g	39.2	47.7	37.7	48.9
Stretch at break	mm	2.01	2.00	1.88	2.04
Tear index	Nm^2/kg	8.1	7.3	9.3	7.8
Light scattering coef.	m^2/kg	52.4	53.4	47.0	50.6
TEA	J/kg	533	647	472	675
Fibre width	µm	22.7	22.2	25.2	24.7
Fibre wall thickness	µm	8.1	8.3	9.6	9.4
Fibrillation	%	5.6	5.3	4.4	4.3
Fibre length lwa*	mm	1.48	1.44	1.79	1.61
Fibre length llwa**	mm	2.41	2.34	2.62	2.37
Curl	%	17.3	15.7	12.6	12.7
PEX Fines B	%	31.4	32.9		34.1
PEX Shives	%	0.44	0.19		0.22

* Length-weighted average

** Length-length-weighted average

Table A3. Cont.

		S:HT:DDc-LC-LC		SD-SD-LC-LC+SD	
PFI		After DD	After LC	Latency	Final
Bauer MCNett					
16	%	29.6	23.9	36.7	26.3
30	%	19.5	21.9	19.6	22.6
50	%	13.7	15.0	12.2	13.7
100	%	8.7	8.7	6.3	8.3
<100	%	28.6	30.6	25.2	29.1
BMcN>50 R-K Handsheets					
Apparent density	kg/m^3	393	449	404	445
Tensile index	Nm/g	30.9	38.7	30.0	36.7
Light scattering coef.	m^2/kg	38	36.4	35.1	37
Z-strength	kPa	149	171	139	169
SEM Cross sections					
Fibre wall thickness	µm	2.38	2.36	2.51	2.52
Fibre perimeter	µm	104	104	96	99
Wibre wall area	μm^2	171	174	180	188
Share of split fibres	%	36.1	34.3	18.7	20.1