Review paper

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On the development of the refiner mechanical pulping process – a review

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Abstract: This paper is a review of the development of the mechanical pulping process with focus on refiner-based processes. The intention is to provide an overview of the trends and the major advances in the development of the mechanical pulping (MP) process. The focus is on the development of the entire MP process, rather than the refiner as such. However, when discussing the MP process development, it is inevitable to consider the development of the refiner unit operation briefly. Processes for printing papers based on softwood is mainly discussed, but board processes are discussed briefly as well.

Keywords: mechanical pulp; process development; refining; RMP; TMP.

Introduction

This paper is a review of the development of the mechanical pulping (MP) process with focus on refiner-based processes. The intention is to provide an overview of the trends and the major advances in the process development. Wood handling, chipping, water circuits, and bleaching concepts will not be discussed. Concerning the stone groundwood (SGW) process, only the rejects system will be considered since it has affected the refiner-based process design.

The focus is on the development of the whole mechanical pulping process, rather than the refiner as such. However, when discussing the MP process development, it is inevitable to consider the development of the refining unit operation briefly. A more comprehensive description of the refiner development and principles can be found in e. g. Carpenter (1989) and Sundholm (1999).

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When reviewing all the process combinations and refiner types that have been utilized, several questions arise: What has been the driving force behind all these process combinations? Is there a structured development, or have the processes arisen merely due to trial and error? Can all these system solutions be justified by product specifications, raw material quality or energy efficiency? Is it the mills or the suppliers that have directed the development?

We may be unable to answer all questions objectively, but we will try to shed some light on the relatively short history of refiner-based mechanical pulping.

We will discuss mainly the processes for printing papers based on softwood, but processes for board pulp manufacture will be discussed briefly as well.

There are of course local constraints that affect the process design. The available wood raw material has a large impact on both product quality and process design. Generally, the spruce species are easier to handle and require less energy to attain a given set of strength properties compared to pine and fir species (Härkönen et al. 1989, Varhimo and Tuovinen 1999). Furthermore, for the various sub species of pine, the handling of extractives must be considered more extensively.

The refiner

The first refiner-like equipment (i. e. machines with rotating grinding-discs) 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 *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 newsprint (Eberhardt 1955). Reading the paper presented by Asplund (1953), it is quite clear that he experimented early with lower refining temperatures adapted for printing paper pulp production.

At an early stage, two major types of refiners were developed: double disc (DD) refiners equipped with two counter rotating discs by Bauer, later also by SCA/Sunds Defibrator, and single disc (SD) refiners by Defibrator, Jylhävaara, Sprout Waldron and Hymac (Carpenter 1989). Two design concepts were introduced to increase the capacity of a single refiner. The first was the Twin refiner, essentially two SD refiners in one, developed by Sprout Waldron. The first mill installation involved a 45″ refiner in the Grand´Mère Mill, Canada, (Jones 1968). The second concept was the conical disc (CD) refiner developed by Defibrator. The first mill installation in the Hallsta mill, Sweden, involved a 70″ CD refiner (Tistad and Görfeldt 1981).

During this early period of refiner mechanical pulping, the process was often referred to as *refiner groundwood* or *super groundwood*. Later, the process and the pulp produced were referred to as refiner mechanical pulp (RMP). The first commercial RMP process for printing paper was started-up in 1956 at the Lyons Falls Mill (hardwood) and Diamond Match Mill (Softwood), USA (Evans 1956). In the beginning, refiners for paper production were non-pressurized (open discharge) and operated at relatively low consistency (below 15 %), but it was soon realized that higher refining consistency was beneficial for pulp quality development (Holzer et al. 1962).

The breakthrough for refiner-based processes occurred when pressurized chip refiners were introduced (Asplund and Bystedt 1973, Charters and Ward 1973). Strength properties of the produced pulp were much higher, and the shives content was 70–90 % lower compared with RMP. The largest step in the refiner development during the 1970’s was the introduction of pressurized preheating prior to pressurized primary refining. This process was called thermomechanical pulping (TMP) (Asplund and Bystedt 1973). In the beginning, open discharge machines were utilized in the subsequent refiner stages. The first TMP refiner for market pulp production was started in the Rockhammar Mill in Sweden 1968 (Ahrel and Bäck 1970). The first large TMP-lines for newsprint were started-up simultaneously in 1974 in the Hallsta Mill, Sweden (Arnesjö and Dillén 1975) and in the Newberg Mill, USA (Strom 1975). For a period of time, some mills operated a process with pressurized preheating followed by open discharge refining, sometimes referred to as TMR (Wood and Karnis 1975, Peterson et al. 1975, Oksum 1983).

It was considered that the optimal TMP refining temperature was between 120 and 130 °C (Atack 1972, Asplund and Bystedt 1973, Higgins et al. 1978). Later, it was realized that, at least for spruce, 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 1983). The increased refining pressure made it possible to recover steam from the refiners for paper drying without steam compressors. The Kaipola mill was first to install a reboiler without steam compressors in 1980 for the production of clean steam (Huusari and Syrjänen 1981). Steam recovery made the production cost for refiner pulp competitive with SGW (Ulander 1985). The first two-stage pressurised TMP line was developed by Jylhävaara and the first mill installation was made at the Kaipola Mill, Finland, in 1976 (Huusari and Syrjänen 1977).

All MP lines for printing paper started up after 1990 in Scandinavia (Saugbrugs, Kvarnsveden, Hallsta, Braviken and Ortviken) have atmospheric preheating. Some processes employ only a short preheating time (5–10 s) at high pressure (5–6 bar) (Sabourin et al. 1997, Nelsson et al. 2017). Processes with atmospheric preheating should actually be referred to as PRMP (Pressurized Refiner Mechanical Pulp), but the acronym TMP is normally used for all pressurized refiner processes today. The first mill installation of a single stage PRMP refiner was started up in the Braviken mill, Sweden in 1982 (Jackson and Åkerlund 1983).

The TMP expansion has been recorded by Leask and later Barnet in a yearly report published in Pulp & Paper Magazine Canada. At the end of the 1970’s, printing paper applications accounted for 82 % of the installed TMP refiners, with the remainder almost equally split between paperboard and market pulp (Data from Leask reviews).

During the 1980’s, the major refiner development was machine size and thereby capacity increased from approx. 5 adt/h to 18 adt/h for two stage processes (Leask 1989). Control systems for refiners also improved considerably during this decade (Dahlqvist and Ferrari 1981, Oksum 1983).

In the 1990’s the manufacturers of high consistency (HC) refiners had been consolidated to Valmet and Andritz. During this decade, Valmet developed the large conical disc refiner, (CD82) and the large double disc refiner (RGP68DD), whereas Andritz developed the Twin refiner up to Twin-66. Andritz presented the RTS process in 1997 based on optimized **R**etention time, refining **T**emperature and rotational **S**peed (Sabourin et al. 1997) and the first mill installation was started-up in the Perlen Mill, Switzerland, in 1996 (Aregger 1997).

Since the mid 1990’s, not much has happened with the HC refiner design, except that Andritz introduced the

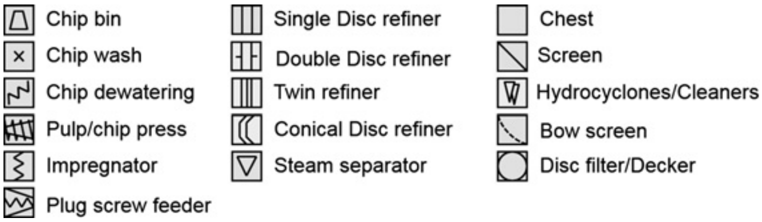

Figure 1: Symbols used in block diagrams.

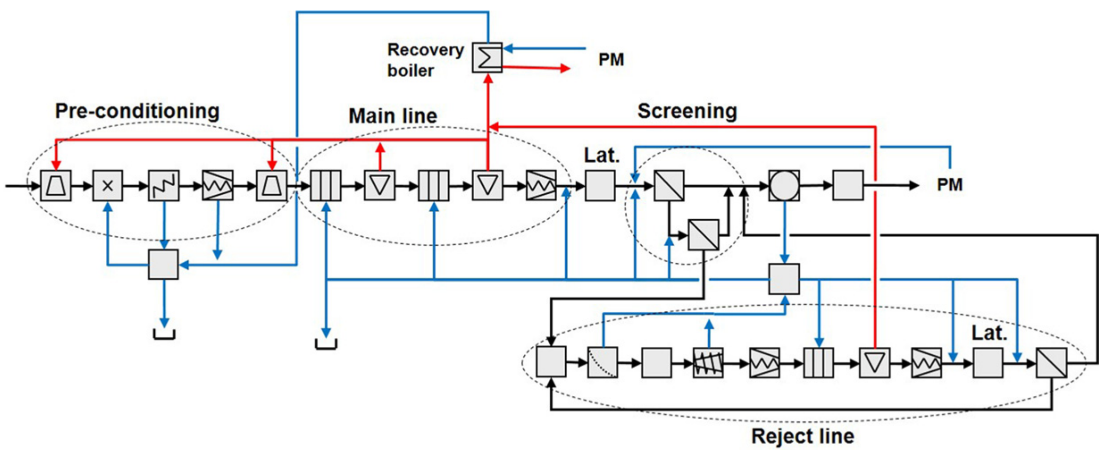

Figure 2: Overview of a typical TMP process. Latency chests are denoted "Lat." Red lines are steam and blue are water.

largest HC Twin refiner model TX68. However, process design, segment design and refiner control have improved refiner performance in terms of loadability, operational stability, production capacity and pulp quality (e. g. Vikman et al. 2003, Karlström et al. 2018).

Mechanical pulping systems

Symbols used in block diagrams are explained in Figure 1.

Almost all refiner-based MP lines consists of four major process sections shown in Figure 2: chip preconditioning, main line refining, fractionation/cleaning and reject treatment. An important additional unit process is the latency treatment after all HC refiners. The process sections will be discussed in detail below. Franzén (1986) described the status of the mechanical pulping process at the time, covering the mentioned process sections as well as other aspects, such as raw material selection and bleaching.

In the block diagrams below, the presteaming, chip washer, plug screw feeders, chests, and steam separators have been omitted to make the figures easier to read. Rejects dewatering is symbolized by a screw press only.

Chip pre-conditioning

The wood chips must be hot and moist to attain proper fibre separation in the refining process. Therefore, wood chips are presteamed and then immediately submerged in the chip washer to remove heavy debris such as sand, grit, gravel, etc. After the chip wash, chips can be preheated one more time before refining. The presteaming and chip washing operations have not changed much over the years and will not be discussed further.

As an integral part of chip conditioning, water impregnation of chips using a heavy duty plug screw feeder or an Impressafiner feeding into an impregnating column has been used to advantage in various parts of the world. It is one way to deal with fluctuations in the moisture content of the incoming chips and ensure that chips with a more or less constant moisture content are fed to the refiners (Hartler 1977, Fournier et al. 1991). This kind of heavy compression pretreatment of chips before refining can also reduce specific refining energy by approximately 10 % and removes 30–40 % of the wood extractives as well as some brightness lowering substances (Robinson 1964, Thornton and Nunn 1978, Costantino and Fisher 1983, Tanase et al. 2010, Nelsson et al. 2012). A comprehensive review of mechanical chip pretreatment has been made by Gorski et al. (2010).

Chemical treatment in conjunction with refiner pulping has been used since the Asplund process was introduced (Asplund 1953). Chemicals have been added in trials and in mill operations in almost all imaginable process positions. However, it is beyond the scope of this review to provide a complete picture of all work in this area. The intention with chemical additions has mainly been to improve pulp quality and/or reduce specific energy. In addition, adding alkaline sulphite to the refiner reduced segment corrosion, which was a problem with the alloys used in the early days of RMP production (Beath et al. 1973, Rankin 1977). By far the most utilized chemicals in mechanical pulp production are bisulphite or sodium sulphite. Impregnation of chips with charge levels of 10–30 kg/bdt (as Na_2SO_3) before pressurized preheating (120–135 °C) and refining is usually referred to as chemithermomechanical pulping (CTMP), which is not discussed in detail in this review. During the 1980's the CTMP production capacity started to expand rapidly, especially in Canada (Sharman 1989). In the early days of RMP and TMP some mills added sulphite in the process (e. g. Cochrane and Crotogino 1965, Beath et al. 1973).

Chemicals have been added to the process in different positions, e. g. in an impregnator or to the refiner dilution water (Dorland et al. 1962, Costantino and Fisher 1983). Addition of sulphite to the refiner dilution water was later referred to as dilution water sulphonation (DWS) (Richardson et al. 1990). Chemical treatments in conjunction with MP have been more comprehensively summarized by e. g. Lindholm (1979) and Mackie and Taylor (1988). When sulphite is added before the primary refiner, the light scattering of the produced pulp is reduced (Atack et al. 1977, Nelsson et al. 2017). This effect is lower when sulphite is added after the primary refiner stage, referred to as *Interstage sulphonation* (Heitner et al. 1982), or the *OPCO process* (Barnet et al. 1980). The lowest reduction of light scattering is attained if the chemical treatment is performed on a long fibre fraction (e. g. screen rejects) prior to refining, referred to as the *Monopulp process by* Gavelin (1980) and as *long fibre sulphonation* by Gummerus (1983) and Franzen (1983). The loss of light scattering from sulphite chip pretreatment can also, to some extent, be reduced by an increased refining intensity (Sandberg et al. 2018b).

Chemical treatments were not common in MP mills for printing papers from the late 1980's and forward. However more recent work has shown that it can be beneficial for energy efficiency and pulp properties to include a chemical addition in the process (Johansson et al. 2011, Nelsson 2016).

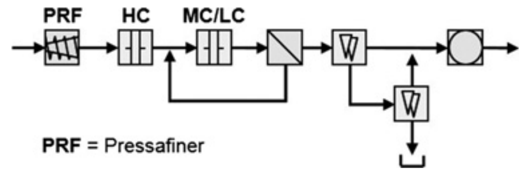

Figure 3: Early RMP process with second stage MC/LC refining and screen rejects fed back to LC refining; Redrawn from Eberhardt (1955).

Main line refining

In the early RMP lines, main line refining was performed in two stages after chip pretreatment in a Pressafiner, Figure 3. The primary refining was done at higher consistency (first at 15 %, later above 20 %) and the secondary refining was performed at low consistency (LC, 4–6 %) or medium consistency (MC, 7–15 %) (Eberhardt 1955). During the 1960's it became more common to install processes with two stages of HC refining often followed by a third low consistency refining stage, but without a Pressafiner.

The change to two stage HC refining was driven by the fact that it was difficult, at least with the early DD refiners, to apply the load needed to achieve reasonable pulp quality in a single non-pressurized HC stage. To be able to maintain high refining consistency, Atack and Wood (1973) pointed out that it was necessary to perform the main line refining (non-pressurized) in two or three stages. 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.

It was realized early in the RMP history that 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 Dahlqvist 1973, Falk et al. 1987, Heikkurinen et al. 1993, Stationwala et al. 1993). An expression sometimes used is that the primary refiner sets the "fingerprint" of the produced pulp. The idea of separating defibration and fibrillation into different refining stages was suggested early (Neill and Beath 1963). However, at the time, it was not known which refining conditions were optimal for the two processes. Research during the 80's showed that it was beneficial to do 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 Advanced TMP (ATMP) process, Figure 4, in cooperation with Norske Skog (Sabourin et al. 2003, Hill et al. 2009). An ATMP process was started in Steyrermühl, Austria in 2011. In contrast to

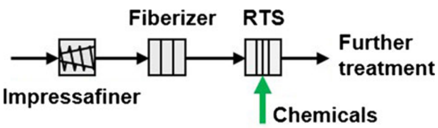

Figure 4: Example of ATMP process, Redrawn from Hill et al. (2009).

this, it has been shown that high quality pulp can be produced with low specific energy in a single stage DD68 refiner operated at high temperature (Muhic et al. 2010).

Wood can be characterized as a viscoelastic material, and therefore the strain rate that the wood and fibre material is subjected to will affect property development and energy efficiency (Becker et al. 1977, Salmén and Fellers 1982). Different concepts for improved efficiency, based on this fact, have been presented over the years. Miles et al. (1991) suggested that it was beneficial to apply a relatively low amount of energy in the primary refining stage at high intensity and the major part of the energy at low intensity in the second refining stage. On the other hand, Sabourin et al. (2003) suggested that initial defibration should be made at low intensity and in the second stage, the major part of the energy should be applied at high intensity. Intensity is a concept that is not easy to define exactly but it can be described as the *harshness* or *severity* of refining and can to some extent be connected to the strain rate (Sandberg et al. 2018b). It was first introduced for low consistency refining (Lewis and Danforth 1962) and later adapted for HC refining (Miles and May 1989).

Main line refiners have been combined in several ways, Figure 5. Since the chip refiners usually could be loaded more than the second stage refiners of the same size, one concept was to supply one second stage refiner with pulp from two primary refiners, Figure 5B or three secondary refiners fed by four primary refiners, Figure 5C. The main purpose of these configurations was to be able to use one motor size and one refiner size and load all stages as much as possible.

Considering the main line design, there are rather distinct differences between North American practices and the rest of the refiner world. Today, almost all processes in North America have two (or more) stages of main line refining, whereas the installations outside North America are more varied consisting of:

– 36 % single stage operations dominated by double disc refiners
– 45 % two stage operations, Figure 5a
– 4 % two primary refiners feeding to one secondary refiner, Figure 5b
– 14 % more complex configurations – usually four primary refiners feeding three secondary refiners, Figure 5c

In North America, where the power grid frequency is 60 Hz, single disc refiners rotate at 1800 rpm while large double disc refiners rotate at 2 × 1200 rpm, which gives a Δrpm = 600 (DD-SD). In Europe and many other parts of the world, where the power grid frequency is 50 Hz, single disc refiners rotate at 1500 rpm, unless they have been equipped with a gear box to increase the rotational speed, while double disc refiners rotate at 2 × 1500 rpm, which gives a Δrpm = 1500 (DD-SD). These differences between North American and European operation are sufficient to account for some of the variation in observations regarding pulp quality and specific energy between North American and European refining installations (Bergström et al. 1970, Sundholm et al. 1988, Cort et al. 1991).

Single stage main line refining

The first RMP lines were usually operated 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).

At the time, it was difficult to load the 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 modified the feeding to the Bauer DD refiners, which made it easier to run pressurised single stage DD refiners to low freeness values (below 100 ml

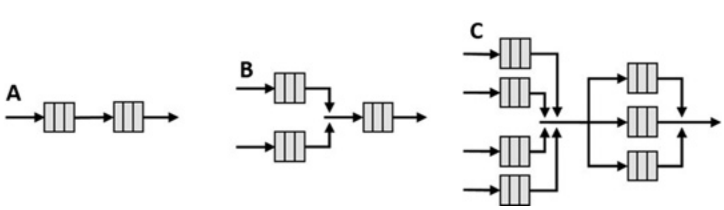

Figure 5: Three examples of main line refiner configurations.

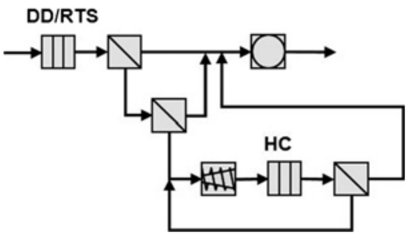

Figure 6: Example of process with single stage main line refining, normally there are several parallel chip refiners.

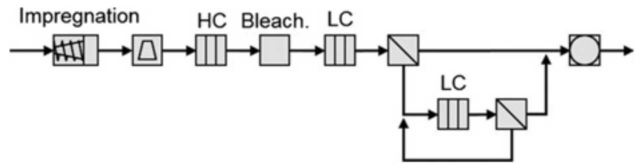

Figure 7: An example of a modern CTMP process design with LC refining as second stage in the main line and for reject refining; Redrawn from Peng et al. (2018).

CSF) (Mannström 1980). The first pressurized single stage TMP line was started in the Summa mill, Finland, in 1977 (Skinnar 1979).

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.

Today, single stage main line refining, for printing paper, is almost exclusively utilized in processes with high intensity chip refining such as DD or RTS. A single stage design with a modern slotted screening system is shown in Figure 6. Examples of such systems are Perlen (RTS) (Aregger 2001) and Kvarnsveden (DD) (Ferritsius 2019). For printing paper, only a few single stage SD refiners have been in operation. Some examples are: Kenogami (Mills and Beath 1975), Donnacona (Wood and Karnis 1975), Hallsta CD70 and RLP58 (Tistad and Görfeldt 1981), Kvarnsveden CD82 (Ferritsius et al. 2016), Braviken RLP58 (Sandberg et al. 2017a). The process in Braviken is in production.

Main line low consistency refining

LC refining was used at an early stage for reject refining and post refining in SGW lines (Klemm 1957, 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 shives reduction and for a final freeness adjustment.

In the early days of RMP, LC refining was used for second or third stage refining in the main line, often in combination with screen rejects refining, Figure 3, (Eberhardt 1955) but it was also used for separate reject refining (Gavelin 1966). During the 1980's it was widely accepted that mechanical pulps required lower intensity during LC refining to avoid extensive fibre length reduction (Levlin 1980, Robinson et al. 1985), however, Kurdin (1974) pointed it out earlier.

During 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). At the time, the incentives for such installations were a cost efficient 10–15 % increase of production capacity and reduced specific energy to a given freeness. LC refining of mechanical pulp has been thoroughly described e. g. by Welch (1999), Luukkonen 2007, Andersson (2011). For LC refining, the energy consumption for a given tensile index increase or freeness reduction is approximately half compared to HC refining. However, LC refining develops fibres differently compared with 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, resulting in pulps with lower light scattering compared to HC refining (Ferritsius et al. 2016, Sandberg et al. 2017a). It is preferable to combine LC refining with high intensity chip refining to attain light scattering level equivalent to that achieved by SD HC refining (Andersson et al. 2012, Sandberg et al. 2017a).

Modern CTMP lines, mainly based on hardwood, utilize LC refining in the main line and for the treatment of rejects, Figure 7 (Guangdong et al. 2011, Peng et al. 2018).

Latency treatment

After HC refining, fibres are twisted and curled as well as entangled in flocs. When the pulp leaves the high temperature conditions, the deformations are frozen into the fibre structure and the phenomenon is referred to as "latency" (Beath et al. 1966). Usually, latency is removed in agitated chests at approximately 3 % consistency, 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. Beath et al. (1966) and Welch (1999) showed that conventional latency treatment can be replaced with an LC refining stage at high enough temperature.

Fractionation

Mechanical pulp has almost always been further treated after the main line process. The pulp leaving the main line refiners or grinders usually contains material, such as unseparated fibres (shives, slivers), poorly treated fibres, sand, bark, etc. that must be upgraded or discarded from the process. Depending on the quality demands on the produced pulp, more or less advanced equipment is needed for separation of the unwanted material (Martin 1982, Hautala et al. 1999). The separation of pulp into two streams, or more, with different properties is referred to as fractionation. Fractionation can be made according to any pulp property, such as fibre length, shives content, fibre wall thickness, etc. Usually a specific fraction of the pulp is removed for upgrading prior to recombination with the main flow or for utilization in another product. A special case of fractionation is cleaning, 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, we will use the term *fractionation* for processes where a larger part of the pulp is separated for rejects refining and *cleaning* for process where the reject is sewered. We use the term screen room for the whole fractionation and cleaning systems.

Over the years, two major equipment categories, screens and hydrocyclones, have been 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 MP processes, screens are seldom used for cleaning, as they are in recycled fibre processes. Generally, screens separate particles according to size, e. g. fibre length, and hydrocyclones according to specific surface and density (Wood and Karnis 1979, Karnis 1982, Sandberg et al. 1997, Ouellet et al. 2003). Two major types of apertures have been utilized in screens; holes and slots. Slotted screen baskets have higher shives removal efficiency (Hooper 1987). Both screens and hydrocyclones are normally arranged in two or more stages to improve the selectivity of the separation (Steenberg 1953, Friesen et al. 2003). Undoubtedly, the screen room is the process section that have had the largest number of configurations.

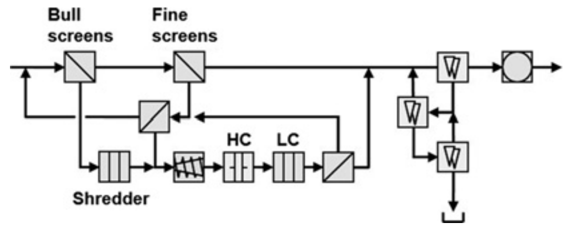

Figure 8: Rejects system at Lufkin Mill, USA; Redrawn from Witherell (1968).

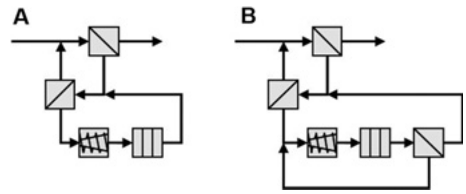

Figure 9: Examples of groundwood fine screening and rejects refining systems **A:** One of the most common early configurations. **B:** System with a separate rejects screen; Redrawn from Beath (1971).

Since similar system designs have been utilized for SGW, RMP and TMP, we will discuss them together.

For a long time, groundwood pulps were only fractionated with non-pressurized screens (Centrifugal screens) most often fitted with hole screen plates. Pressure screens were introduced in the SGW processes in the late 1950's (e. g. McLenaghen et al. 1959). SGW processes always have two screening systems; In the first, larger wood residues (slivers) are removed with coarse screens (bull screens) for further treatment. After coarse screening, the pulp is fractionated in a fine screen system. One example of a complete groundwood screen room is shown in Figure 8.

For the fine screening, numerous combinations have been utilized (Steenberg 1953), however, the most common fine screening configuration until the 1990's was two-stage screening, Figure 9A, with the second stage accepts fed back to the primary screen feed or to the bull screen feed. In processes producing pulp for rotogravure, double screening (two screens in series) was often utilised in the fine screening system (Chapman and Allan 1970, Dillén et al. 1973).

In processes producing pulp for rotogravure, double screening (two screens in series) was often utilised in the fine screening system (Chapman and Allan 1970, Dillén et al. 1973).

In SGW processes, refined rejects were often directed to the second stage screen feed. However, Beath (1971) showed that it was more efficient (debris reduction vs. re-

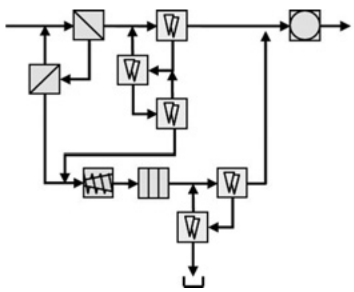

Figure 10: Groundwood fractionation and cleaning system with no screening, just cleaning of the refined reject; Redrawn from Richardson (1969).

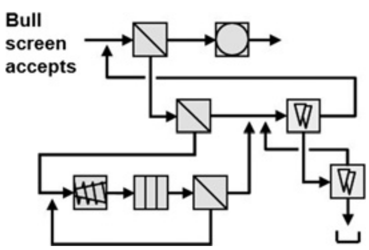

Figure 11: Groundwood screen room with hydrocyclones only on second stage screen accepts, Laurentide Mill, Canada; Redrawn from Racine (1968).

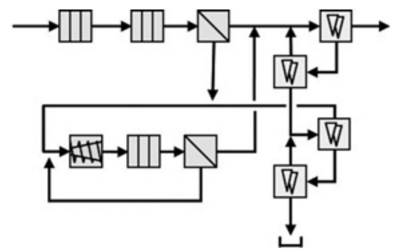

Figure 12: Main line hydrocyclone system utilised for both fractionation and cleaning, TMP line at Hallsta Mill, Sweden; Redrawn from Arnesjö and Dillén (1975).

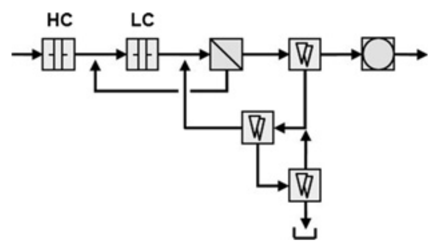

Figure 13: Early Bauer RMP process at the Kenogami Mill, Canada; Redrawn from Neill and Beath (1963).

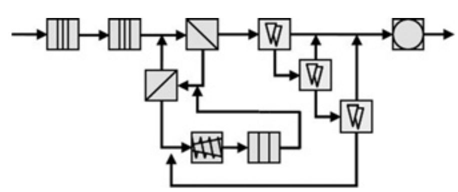

Figure 14: A Sprout Waldron RMP process at the Kawerau Mill, New Zealand; Redrawn from Rankin (1977).

fining energy) to have a dedicated rejects screen as shown in Figure 9B. When rejects refining was improved during the late 1960's, it was realised that reject screen accepts could be fed forward, Figure 8 (Witherell 1968).

During the 1950's hydrocyclones were introduced in the SGW screen rooms, which improved the removal of specks, chops (small cubical shives) and sand (Klemm 1957). The hydrocyclone systems were either utilised only for cleaning, Figure 8, or for fractionation and cleaning, Figure 10. After HC rejects refining had been introduced in the late 1960's, Richardson (1969) recommended omitting screening and only have cleaning of the refined rejects to minimize fibre length reduction, Figure 10.

Usually hydrocyclones were arranged with the accepts fed backwards in cascade to the previous stage, as in Figures 8 and 10. In some installations, at least with RMP processes, accepts were fed forward as shown in Figure 14. In some mills (both SGW and RMP) hydrocyclones were only utilised in the reject system, Figure 11.

The hydrocyclone systems sometimes have a broken cascade in which the second or third stage accepts are combined with screen rejects before rejects refining, Figure 12.

When refiners were introduced for production of mechanical pulp, fractionation systems similar to those used for SGW were adopted (Klemm 1957, Rydholm 1965, Gavelin 1966). In the early processes, rejects were usually fed backwards to the main line after primary refining, Figure 13. Later, it became more common to install dedicated rejects refiners, Figure 14.

Since the non-pressurized refiners produced a relatively large amount of chops, and the removal efficiency of those was low for screen baskets equipped with holes, hydrocyclones were usually needed to achieve a sufficiently clean pulp.

When TMP was introduced, shives content was reduced to such an extent 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). It was also suggested to replace fractionation and cleaning with LC post refining (Gustafsson and Vihmari 1977). That concept was however not pursued further until Sandberg et al. (2017b) showed that newsprint for modern high-speed offset printing can be produced without any fractionation or cleaning in the pulp mill.

It has also been suggested that more energy should be applied in the main line and thereby the screens could be omitted and only hydrocyclones used for fractionation (Ahrel 1973, Hofmann 1975). Even earlier, Holzer et al. (1962) showed that RMP for newsprint could be produced with a three stage HC-HC-LC process (DD HC refiners) without screens and using only hydrocyclones. However, such a concept will require larger disc filter capacity.

A large improvement in the development of the screening process occurred when wedge wire slotted screen baskets were introduced during the 1990's. The large improvement in shives removal efficiency rendered the hydrocyclone systems superfluous, at least for newsprint, and they were removed in many mills (Cannell 1999). Some mills removed the hydrocyclones earlier, e. g. the Hylte Mill, Sweden, (Ulander 1985), the Ortviken Mill, Sweden, (Engstrand et al. 1987) and the Summa Mill, Finland, (Nopanen 1989). With the introduction of modern slotted screens, the system design of the screening process also changed from feed backward to feed forward of second stage accept which led to the most common screen configuration of today, Figure 6.

Advanced fractionation systems

A few examples of processes incorporating more complicated fractionation systems are worthy of mention. The Ortviken mill, Sweden, has a complex multi-stage screening system using a combination of hole and slotted screens, which according to Asplund et al. (2009) is advantageous for the removal of coarse fibres. The Braviken Mill, Sweden (Sandberg et al. 1997) and the Saugbrugs Mill, Norway, (Kure 2018) use a combination of screens and fractionating hydrocyclones which is beneficial for the removal of thick-walled latewood fibres (Sandberg et al. 1997, Kure et al. 1999). Another process based on extreme fractionation is the interstage screening process (ISS), in which fibres and fines are separated already after primary refining and the fibre fraction is subsequently refined in a second HC refining stage after dewatering, Figure 15 (Ferluc et al. 2010, Bousquet et al. 2016). After the fibre fraction refining, the pulp is processed in a conventional rejects system, or the rejects (shives/coarse fibre) from barrier screening are refined in the fibre fraction refiner stage. In this connection, it is very important to understand at what freeness level the primary refining should be terminated and this will, of course, depend on the wood species involved and final pulp quality requirement.

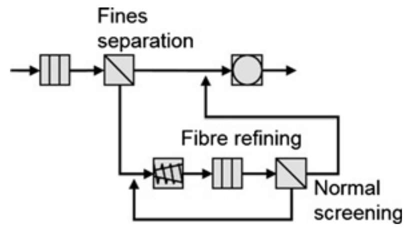

Figure 15: Inter stage screening (ISS) process. Fibres and fines are separated in the first screening system and shives/coarse fibres are removed in the second screening stage; Redrawn schematically from Bousquet et al. (2016).

These processes are more complicated and thus have higher capital and maintenance costs, but might be beneficial for pulp quality and energy efficiency. There are some results showing an energy reduction potential of the order of 10–20 % (Sandberg et al. 2001, Nurminen and Liukkonen 2001, Bousquet et al. 2016).

Rejects refining

Refining of rejects for recombination with screen accepts was not common practice in groundwood mills until the 1930's. Before this time, the screen rejects were sewered, at least in North America (Edwards 1964). The early refiners were gravity fed open discharge units, usually operating in the consistency range 4–15 % (de Montmorency and Koller 1957, Klemm 1957). On the other hand, Gardiner and Stafford (1955) stated that it was better for refiner stability and pulp quality to perform the rejects refining at very low consistency, approx. 1 %. However, most studies showed that it was preferable to perform the rejects refining at high consistency. It should be noted that before the 1960's, 15 % was considered as high consistency in rejects refining, whereas today 7–15 % is considered medium consistency and > 30 % is considered high consistency.

In the early RMP processes, rejects refining was performed at low to medium consistency (4–15 %), Figure 3. From the late 1960's, rejects refining was usually performed at high consistency for the most efficient pulp quality development, (e. g. Wild 1971). As TMP was introduced, it was found that a large proportion of the fibres contained in the long fibre fractions of main line TMP were poorly developed and that these fibres needed to be removed from the main stream and reprocessed separately in a dedicated refiner in order to improve their bonding potential. (e. g. Jackson and Williams 1979, Mohlin 1989, Corson and Lee 1990).

The concept with combined rejects and second stage main line refining that was performed with LC refiners

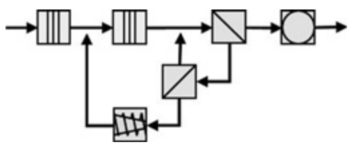

Figure 16: TMP system from 1980's with screen rejects fed back to second stage main line HC refining; Redrawn from Ulander (1985).

in the early Bauer RMP installations, was also applied in HC refiner lines supplied by Sprout Waldron (Jones 1968, Ulander 1985, Fjerdingen et al. 1997). The main line consisted of two or three refiners in series and the screen rejects were introduced before the second refining stage, Figure 16. This process concept however is no longer in widespread use.

For printing paper, the most common rejects treatment today is single stage HC refining. Other approaches include two stage HC refining (Viljakainen et al. 1997, Amiri et al. 2016, Sandberg et al. 2017a) and a combination of HC and LC refining. The combination of HC and LC refining of rejects has been shown to improve pulp properties and efficiency (tensile index – specific energy) (Lansford 1979, Sandberg et al. 2017a). Viljakainen et al. (1997) evaluated LC-HC refining on rejects, but found no positive effects of the combined LC and HC refining. However, the applied specific energy in that LC refiner was low compared to the specific energy reported by Sandberg et al. (2017a). HC-LC refining of rejects was also applied in some groundwood mills (e. g. Witherell 1968, Ferritsius and Ferritsius 1997).

As mentioned above, LC refining of rejects was common in the early RMP lines. Nowadays, this is rare and for printing paper, the TMP mill in Skogn, Norway, is the only mill in operation, to our knowledge, that utilises LC refiners for rejects refining (Imppola et al. 2013). However, in the Skogn mill, LC refining is carried out on mixed main line pulp and rejects. In Braviken, the same concept has been introduced recently, but the screen accepts are further fractionated in hydrocyclones with the rejects being refined in HC refiners.

In contrast to the established idea of mechanical pulping processes containing rejects separation and refining, Ferritsius et al. (2014) showed, based on thorough pulp quality comparisons of a large number of TMP lines, that the same pulp quality can be reached after single stage high intensity main line refining as final pulp from a TMP line with two stage SD refining, screening and rejects refining. Sandberg et al. (2017b) produced paper on a high-speed paper machine with a high efficiency TMP process without any fractionation. The produced paper performed even better in printing than the normal newsprint produced with a conventional SD TMP process.

Post refining

Post refining of groundwood pulp with pump through refiners was introduced during the 1960's, mainly as a final adjustment of paper quality. An applied specific energy of 40 kWh/t gave a reduction in shives content of 50 % and increased burst and surface smoothness by 10–20 % (Richardson 1969, Kurdin 1974). Post refining was also a low-cost alternative to increase groundwood production (Hoholik 1958). It was also used to upgrade a newsprint furnish to higher quality grades (Brandal and Hauan 1970). Kilpper and Baumgartner (1977) showed in pilot scale that it was better to only post refine the longest fibres.

In some mills, news grade pulp is upgraded to light-weight coated (LWC) and super calandered (SC) quality by HC post-refining and peroxide bleaching (e. g. Asplund et al. 2009).

Process design approaches

Some process concepts can be distinguished from the most common process design shown in Figure 2. We have tried to group these designs according to, in our judgement, an intention or approach in the choice of process configuration. This is our subjective classification, and another grouping might of course be possible.

Main line approach

One idea is that the most economical process with good fibre development is attained by doing as much of the fibre development as possible in the main line refining and only having a low reject rate with LC refining on the reject. Such a process, with three CD82 HC refiners in series, was in operation for several years in the Port Hawkesbury Mill, Canada, Figure 17, (Mokvist et al. 2005). Nowadays, the mill has a more advanced two stage HC reject refining

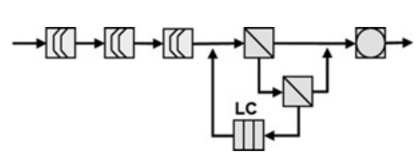

Figure 17: Example of process with rejects LC refining – Port Hawkesbury, Canada; Redrawn from Mokvist et al. (2005).

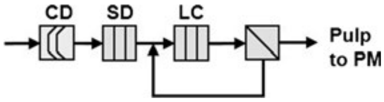

Figure 18: TMP process in Skogn, Norway; Redrawn from Imppola et al. (2013).

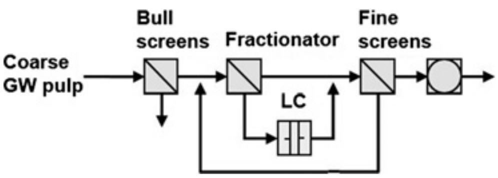

Figure 19: Fractionation and refining of coarse groundwood pulp at the Manistrique Mill, USA; Redrawn from Hoholik (1958).

system for the production of SCA++ on the same refining line (Amiri et al. 2016). The Skogn Mill, Norway, has a similar process, but with two stage HC refining (CD+SD) and LC refining on combined main line pulp and rejects, Figure 18, (Imppola et al. 2013).

Fractionation approach

Much research has been made on concepts where the refining is separated into a primary refining, after which the pulp is fractionated into a coarser fraction sent to further refining and a finer fraction that is fed directly to dewatering. Such a process concept was first suggested for refiner processes by Luhde (1966). However, it was used even earlier in groundwood production where a coarse groundwood pulp was produced, coarse-screened and fractionated using a vibrating screen, Figure 19. The screen rejects (roughly 50 % of the bull screen accepts) were refined in three DD refiners (Hoholik 1958). The refined rejects were combined with the vibrating screen accepts and fed to the fine screens. The fine screen rejects were fed back to the vibrating screen feed.

The refining process is strongly heterogenic (Reyier Österling 2015), 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, Corson et al. 1995). One major problem with this idea is how to achieve the fibre fractionation with high efficiency. Screens have a low ability to separate fibres with regard to fibrillation and bonding ability but can to some extent separate fibres according to coarseness (Ämmälä 2001). Hydrocyclones have higher separation efficiency, but they suffer from the large disadvantage that very low consistency is needed to

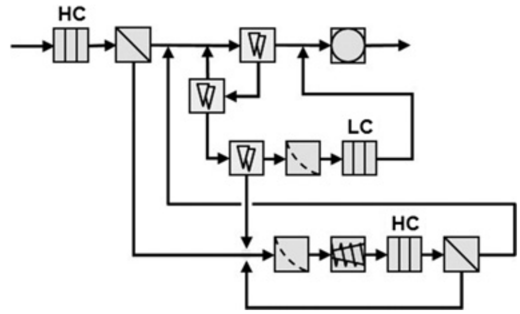

Figure 20: Noss Advanced Mechanical Pulping Process; Redrawn from Shagaev and Bergström (2005).

achieve good fractionation and thereby much larger disc filter capacity is required. (Karnis 1982, Mohlin 1989, Sandberg et al. 1997, Kure et al. 1999, Wakelin et al. 1999, Sandberg et al. 2001, Ouellet et al. 2003).

One extreme example of this approach is the Noss Advanced Mechanical Pulping Process (NAMP), Figure 20, which was developed to maximize fractionation efficiency and optimize the refining conditions for different fibre fractions (Shagaev and Bergström 2005). The concept utilizes LC refining on the intermediate hydrocyclone fraction (enriched in transition wood fibres) which can withstand a high load in LC refining, whereas late wood fibres (third stage hydrocyclone rejects) and screen rejects are refined at HC. The process has been evaluated in mill scale, (Sandberg and Shagaev 2011) but is not in continuous operation.

Defibration/fibrillation approach

Another approach is the idea of performing defibration and fibrillation in separate machines using different conditions, as mentioned in the "Main line refining" section above. This concept was proposed by Neill and Beath (1963). Based on similar ideas, Valmet developed the Thermopulp process (Höglund et al. 1997) and later, Andritz developed the ATMP process, Figure 4, in cooperation with Norske Skog (Sabourin et al. 2003, Hill et al. 2009). The Thermopulp concept was difficult to run due to low disc gap in the second stage refiner operating at 7–8 bar pressure (authors experience from the Braviken mill) and there are unfortunately no reports, so far, from the only mill installation of a full ATMP process. However, the concept of separating the defibration and fibre development seems to be a good way to further reduce the specific refining energy. More mill experiences are however needed in this area.

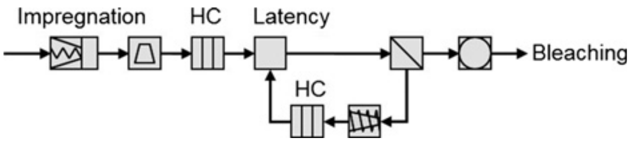

Figure 21: CTMP process; Redrawn from Jussila et al. (1999).

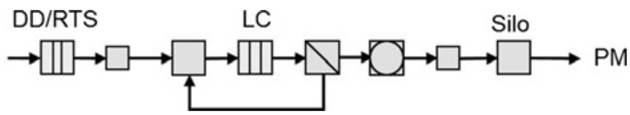

Figure 22: Simplified process concept.

System simplification approach

Reducing process complexity has, in some cases, represented a driving force for system development, motivated by reduced capital cost and easier process control (e. g. Ulander 1985). Some TMP and CTMP lines were built with the process configuration outlined in Figure 21. (Jussila et al. 1999). It is a simplified process with low capital cost since there is no separate rejects screening or rejects latency chest. Even though this process is compact, it is not easy to have an on-line pulp quality control of the two HC refiners.

The TMP process utilized in Skogn, Figure 18, is also an example of a design that simplifies the process. Sandberg et al. (2018a) have shown that it is preferable to utilize high intensity refining, such as DD or RTS, for this process concept. A process incorporating single stage HC refining and LC refining of primary stage pulp and screen rejects, Figure 22, reduces system complexity and refining energy as well as improves process control. Such a process was evaluated by Strand et al. (1993) and by Sandberg et al. (2018a), the latter involved single stage HC refining with RGP68DD refiners. A similar process has also been in operation at the Boyer Mill, Tasmania, with smaller DD refiners (Bonham et al. 1983).

Discussion

As has been presented above, there are many system designs for MP production. What have been the driving forces for the process development? There have clearly been many different views on what constitutes the best solution for refining efficiency and achieving good pulp quality.

One approach that, in most cases, has not been utilized is controllability. Automatic control of refiner systems is becoming more and more important since manning is being reduced and the demand for stable product quality is increasing. Systems such as those in Figures 5c and 21 where pulps from different refiners are mixed and where the production from individual refiners could not be monitored on-line are not ideal for automatic control. Processes with a small standpipe or pulper after each refiner and a minimal number of large chests, illustrated in Figure 22, are ideal for process control (Blanchard and Fontebasso 1993). TMP processes normally contain large volumes of pulp in different chests, which makes the system very slow. Of course, at least one large chest is needed to minimize the effect of shorter stops in parts of the process. In regions where the electricity has a large variation in price depending on the time of the day, larger pulp storage volumes can be economically motivated.

Another way to classify the processes could be according to final product quality, e. g. newsprint (Coldset), SC/LWC (Rotogravure), etc. We have not chosen to do this classification since there are several different design concepts that have been utilized for high quality grades, e. g. extended main line refining (three stages), more advanced fractionation or extensive post refining.

One thing that is striking when earlier work is examined is the creativity of engineers in designing the fractionation systems. Were all these configurations motivated by thorough development work? Probably not. Since screens and hydrocyclones separate particles according to different properties, it is not a good idea to combine hydrocyclones and screens in an arbitrary way. It is, however, beyond the scope of this work to elaborate on what the optimal design is. Of course, the final product and raw material can influence the fractionation system design.

Proximity to an equipment supplier can affect the choice of process equipment. A mill might prioritize good service from a local supplier before lowest price or best performance.

The future remains uncertain and complex. The shrinking market for printing papers will continue but it will be offset to some degree by an increased production of board and packaging grade pulps, partly due to an increasing demand for this type of pulp but amplified due to pressure from both the public and private sectors to drastically reduce the use of non-biodegradable plastics.

In the early days, considerable effort was made by the pulp and paper producers to develop the refiner mechanical pulping process, sometimes in cooperation with machine suppliers, see e. g. Jones (1968), Mihelich et al. (1972), Peterson and Dahlqvist (1973), Pearson et al. (1977) and Huusari and Syrjänen (1977). In addition, all major R&D Institutes directed considerable efforts towards refiner mechanical pulping. Nowadays there are few industry initiatives and rather limited research activities.

Usually, investments in new production capacity offers an opportunity to integrate process and machine development. The equipment suppliers have a vital role in contributing to the progress of new and improved technology. In recent years the investment in refiner mechanical pulping lines has declined drastically. In summary, it is hard to deny that this will risk limiting the rate of progress of mechanical pulping despite its renewable, high wood yield product characteristics. It will be interesting to see if the pulp and paper industry will manage to reinvest in both the human capital and the industrial capital necessary to build a flourishing business based on renewable mechanical pulp.

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