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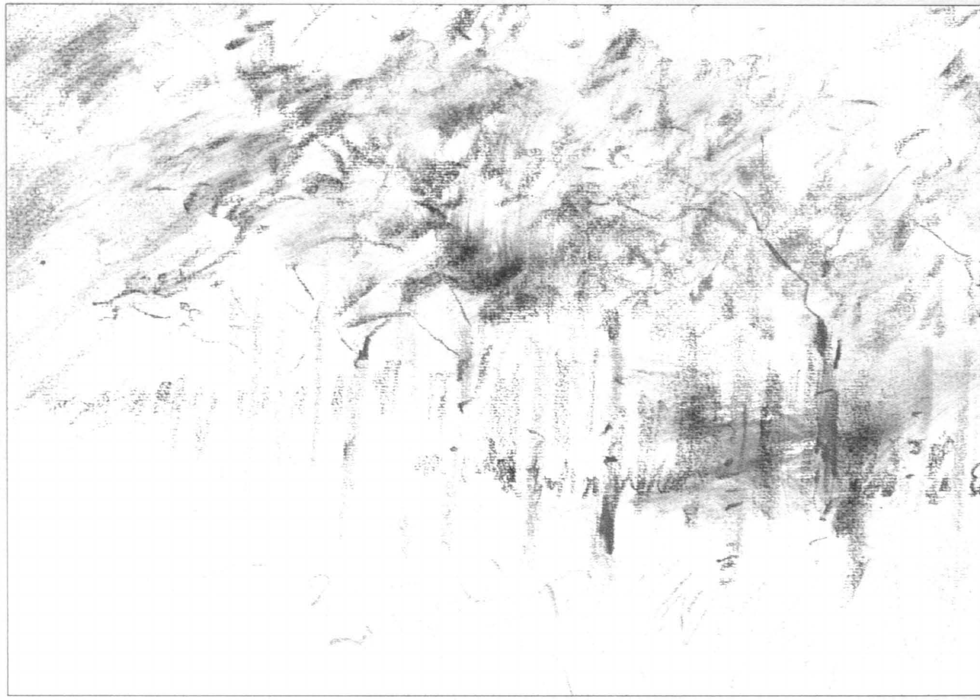

Jukka Tyrväinen

Wood and Fiber Properties of Norway Spruce and Its Suitability for Thermomechanical Pulping

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Jukka Tyrväinen

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The Finnish Society of Forest Science — The Finnish Forest Research Institute

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In the first part of the study, the selected wood and fiber properties were investigated in terms of their occurrence and variation in wood, as well as their relevance from the perspective of thermomechanical pulping process and related end-products. It was concluded that the most important factors were the fiber dimensions, juvenile wood content, and in some cases, the content of heartwood being associated with extremely dry wood with low permeability in spruce. With respect to the above properties, the following three pulpwood assortments of which pulping potential was assumed to vary were formed: wood from regeneration cuttings, first-thinnings wood, and sawmill chips.

In the experimental part of the study the average wood and fiber characteristics and their variation were determined for each raw material group prior to pulping. Subsequently, each assortment – equaling about 1500 m³ roundwood – was pulped separately for a 24 h period, at constant process conditions. The properties of obtained newsgrade thermomechanical pulps were then determined.

Thermomechanical pulping (TMP) from sawmill chips had the highest proportion of long fibers, smallest proportion of fines, and had generally the coarsest and longest fibers. TMP from first-thinnings wood was just the opposite, whereas that from regeneration cuttings fell in between the above two extremes. High proportion of dry heartwood in wood originating from regeneration cuttings produced a slightly elevated shives content. However, no differences were found in pulp specific energy consumption. The obtained pulp tear index was clearly best in TMP made from sawmill chips and poorest in pulp from first-thinnings wood, which had generally inferior strength properties. No dramatical differences in any of the strength properties were found between pulp from sawmill residual wood and regeneration cuttings. Pulp optical properties were superior in TMP from first-thinnings. Unexpectedly, no noticeable differences, which could be explained with fiber morphology, were found in sheet density, bulk, air permeance or roughness between the three pulps.

The most important wood quality factors in this study were the fiber length, fiber cross-sectional dimensions and percentage juvenile wood. Differences found in the quality of TMP manufactured from the above spruce assortments suggest that they could be segregated and pulped separately to obtain specific product characteristics, i.e., for instance tailor-made end-products, and to minimize unnecessary variation in the raw material quality, and hence, pulp quality.

Keywords *Picea abies*, wood properties, fiber properties, thermomechanical pulping, pulp properties.

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Contents

List of Main Symbols and Abbreviations

AB = aktie bolaget (Swedish)
abt. = about
APMP = alkaline-peroxide mechanical pulping
BOD = biological oxygen demand
ca. = circa
CSF = Canadian Standard Freeness
CTMP = chemi-thermomechanical pulping
DBH = diameter at breast height
DCM = dichloromethane
EG = Enso-Gutzeit Oy
EMC = equilibrium moisture content
EPP = Enso Publication Papers division
FPPRI = Finnish Pulp and Paper Research Institute
FSP = fiber saturation point
FT = first-thinnings
HP = horsepower
HW = hardwoods
ISO = International Organisation for Standards
LWC = light-weight coated
MC = moisture content
MT = *Myrtillus* site type
o.d. = oven-dry
OMT = *Oxalis-Myrtillus* site type
OPCO = Ontario Paper Company Process
P200 = passed 200 mesh screen
P28 = passed 28 mesh screen
PGW = pressurized-groundwood
PGW-S= super pressurized-groundwood
PM2 = paper machine no. 2
PM4 = paper machine no. 4
PQM = Pulp Quality Monitor
R14 = retained on 14 mesh screen
R16 = retained on 16 mesh screen
R28 = retained on 28 mesh screen
R30 = retained on 30 mesh screen
R35 = retained on 35 mesh screen
R48 = retained on 48 mesh screen
RC = regeneration cuttings
RMP = refiner mechanical pulp
s.d. = standard deviation
S1 = first secondary cell wall layer
S2 = second secondary cell wall layer
S3 = third secondary cell wall layer
SC = super-calendered
SCAN = Scandinavian Pulp, Paper, and Board – Testing Committee
SEC = specific energy consumption
SEM = scanning electron microscope
SGW = stone groundwood
SM = saw mill
Spp. = specia
SW = softwoods
TMP = thermo-mechanical pulp
vs. = versus
VT = *Vaccinium* site type

Preface

This study on the wood and fiber properties of Norway spruce, and their relevance in thermomechanical pulping originated fully from author´s own interest, as well as professional and educational background. However, it was soon found out that such an investigation has not been carried out to date and was in demand by various Finnish interest groups. The study began in 1991 at the Department of Logging and Forest Products Utilization, University of Helsinki, and was formally completed during my stay at the Centre de Recherche en Pâtes et Papiers, Université du Québec à Trois-Rivières. The empirical part of the study, including e.g. commercial scale pulping trials, has been a co-operative effort between the University of Helsinki and Enso-Gutzeit Oy (Publication Papers Division), Varkaus mills.

I wish to thank my supervisor Professor Matti Kärkkäinen of Jaakko Pöyry Oy and Professor Rihko Haarlaa of the University of Helsinki for their guidance in the project. I would also like to thank my Research Assistant Jari Sirainen, a Forestry Graduate from the University of Helsinki, who provided essential engineering knowledge to the project. Support and co-operation by Director Kari Saramäki, Chief Forester Ilkka Härmälä, Superintendent Tuomo Kärkkäinen and Forest Technician Kari Pulliainen, among numerous other key persons at Enso-Gutzeit Oy Varkaus mills, was greatly appreciated. Moreover, I am thankful to M. Sc. (Tech.) Annikki Heikkurinen of the Finnish Pulp and Paper Research Center, for her help and useful comments.

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During this study I have obtained funding from many sources: Academy of Finland, Finnish Culture Foundation, Veikko and Aune Peltola Foundation and Niemi Foundation have all provided financing for the project, not to forget the stake provided by Enso-Gutzeit Oy.

I want to give my warmest thanks to all the people and organizations, mentioned above or not, who have advanced this study.

I dedicate this book to my wife Sari, who not only gave the inspiration to start this challenging project, but had a great influence on the work being completed. I am also grateful to my son Juho Aleksi, whose presence is always an ever-lasting source of joy and happiness.

Juikonniemi, August 1995

Jukka Tyrväinen

1 Introduction

1.1 Background of the Study Problem Area

This study is about wood quality factors of Norway spruce (*Picea abies* L. Karst.) as a raw material in modern mechanical pulping and related paper products. Norway spruce, grown in its natural habitats in Finland and in other parts of Scandinavia, is generally considered as one of the best available raw-material for mechanical pulping and derived paper end-products such as newsprint, LWC, and SC-papers. This is due to its suitable wood and fiber properties. Furthermore, this wood species is also known to produce the excellent reinforcement fiber, i.e. chemical pulps, producing paper with good strength and printability.

In papermaking, there has been a continuous trend towards an increasing relative proportion of mechanical pulps in high-quality papers during the past few decades. However, not only the relative proportion of modern mechanical pulps in wood-containing printing papers has increased, but its overall quality has increased and is under continuous market pressure due to lower paper grammages, new paper grades, faster and wider paper machines, fiber recycling requirements, and also improvements in the pulping technology (Hoekstra et al. 1991, Höglund and Wilhelmsson 1993, Franzen 1993). The above has been partly possible because of the development of thermomechanical pulp (TMP), which has favourable paper making characteristics for various end-uses. However, the intrinsic properties of wood are the true base for any discussion concerning the pulp quality characteristics that can be achieved from any given raw material (Kurdin 1979, Jackson 1985).

In general, the properties of wood affect thermomechanical pulping in two principal ways. Firstly, continuous variations in wood basic density and moisture content occurring in the chip flow tend to cause accordingly variation in refining consistency, which, in turn, affects pulp uniformity and energy consumption (Michelic et al. 1972, Miles and May 1990, Qian and Tessier 1995). The above negative effects are especially harmful, since they cannot be efficiently offset by any process control variable, such as production rate. However, it seems that these impacts can be increasingly minimized with installation of novel process control systems and segregating wood raw material into more uniform quality groups (Cort et al. 1992, Hill et al. 1993, Williams 1993, Braaten et al. 1993).

Secondly, the obtainable properties of pulp and derived paper end-product largely depend on the kind of wood used (Höglund and Wilhelmsson 1993). In this respect, the greatest influence can be attributed to differences between various wood species (Isenberg 1980, Jossart et al. 1988, Härkönen et al. 1989, Barbe et al. 1993). To date, however, it has become clear that the properties of mechanical pulp obtained from various wood assortments from the same species largely differ (McMillin 1968b, Brill 1985, Kellison and Hitchings 1985, Corson 1983 and 1991, Hatton and Cook 1990, Hatton and Johal 1993). The main factor causing variation in the intrinsic wood properties in a coniferous stem is the age of the growth increment calculated from the pith.

Because of constant economical fluctuations affecting the sawmilling industry and consequently its wood use, an increasing amount of large trees that were originally grown as sawlogs are available for the pulp and paper industry. In many cases pulp and paper industry has been capable to pay the price of sawlogs of its raw material, when the final cost of wood up to mill gate is considered. This represents a relatively new situation in Finland. All the above stress to the fact that, in a present situation in which the allowable annual cut of Norway spruce has for more than a decade exceeded the annual harvest, the pulp and paper industry has much more greater variety of choices than in the past, and not only traditional pulpwood assortments like tree tops, thinnings, poor-quality logs and sawmill residual wood. With respect to natural variation in wood characteristics that occurs in conifers mainly due to wood age and environmental factors, the pulp and paper making potential of Norway spruce is expected to vary accordingly. Despite the above, practically all mechanical pulp mills in Scandinavia have no strategy to segregate their wood raw material from the same wood species with respect to its pulping potential, which, in turn, would facilitate the separate pulping of a specific fiber source. Instead, various spruce assortments are being pulped more or less mixed or uncontrolled.

It is obvious that the opportunities offered by raw material segregation are not yet fully in use. Therefore, it is naturally of interest to determine the important wood and fiber characteristics of Norway spruce with regard to TMP and the properties of such pulp obtained from various raw material sources. The main purpose of this introductory chapter (Chapter 1) is to make out a case for the use of Norway spruce as a raw material in mechanical pulping, and more specificly in TMP. The important wood properties or "wood quality" factors, which might be of interest, when discussing thermomechanical pulp made from Norway spruce, are briefly introduced.

1.2 TMP as a Modern, High-Quality Mechanical Pulp

The principal uses of wood for pulping in Finland are kraft pulp and mechanical pulps, the main end-uses being LWC-, SC-papers, newsprint, and various board products. Although chemical and mechanical pulps cannot be seen as alternative products for end-products, the high price of chemical pulp is pushing the paper makers to increase the amount of mechanical pulp in the furnishes. In addition to reduced furnish cost, the increased proportion of mechanical pulp improves the printing properties of the paper. Reduction of chemical pulp in the furnish is possible because of the improved strength of mechanical pulp, that is, the development in modern mechanical pulps, such as TMP, CTMP, PGW, PGW-S, APMP, and OPCO-process. In the past few decades, the growth in production capacity of mechanical pulps can be largely attributed to refiner-based pulping systems, especially TMP (Jackson 1985, Kurdin 1990, Barbe et al. 1993).

Mechanical pulping processes offer several advantages from an environmental point of view when compared to fully bleached kraft or other chemical pulping processes. Namely, the pulp yield from mechanical processes is always over 90 %, compared to that of chemical processes, being usually under 50 %. Effluents in terms of BOD (biological oxygen demand) are several times higher from a chemical pulp mill. Mechanical pulping process uses about 25 % less fresh water and there are no chlorinated by-product which are either present in the mill effluent or in the pulp. In fact, a closed-loop mills will be soon introduced. Moreover, in the case of baseline mechanical pulps there is no sulfur or odour emission. It is known, that mechanical pulp fiber, especially from generally strong TMP pulps, withstands the wear of recycling better than chemical pulp fibers (Franzen 1993, Phipps 1994). This will be a contributing factor when mechanical pulp makes a strong break-in into the wood-free paper sector. All the above mentioned factors can help in the restoration of the image of paper as an environmentally acceptable product in every respect. However, the high electrical energy consumption and toxic effluent load typical for mechanical pulps is still an unsolved problem.

In general, mechanical pulping processes require more from their wood raw material than chemical processes. In other words, if high quality mechanical pulp is to be manufactured, suitable raw material with great uniformity, is needed. The above can be easily understood from the nature of the process, which is solely mechanical, and from the high yield of pulp from wood. In mechanical pulps, the most important raw-material factor is the species of wood. This refers to all those wood properties, typical to a given species, and with which this species deviate from another species. For instance, the dimensions of fibers are certainly changed during pulping, but the character of wood type remains in the final pulp (Höglund and Wilhelmsson 1993). Although there is a considerable variation in relevant wood and fiber properties within a single species, the variation between wood species is though more significant.

Pure mechanical pulping processes require softwoods as a raw material, if the aim is to produce strong pulp. Hardwoods are used in mechanical pulping processes, but usually with the aid of chemical treatment. Mechanical pulp from pines, is in most cases inferior than that from spruces (see e.g. Lindström et al. 1977, Malinen 1986, Jossart et al. 1988, Härkönen et al. 1989, Barbe et al. 1993). In both Nordic countries and North America, the spruces have been traditionally used for manufacting mechanical pulps. In fact, among conifers, the Norway spruce is considered to be one of the most suitable raw material for mechanical pulping and especially for TMP, which is the topic in this study. It is preferred as it is light in color, has slender fibers and low extractives content yielding pulps with good strength, optical and printing properties. Though, the specific energy consumption to a given freeness level or pulp strength is relatively low (Brill 1985, Hartler 1985).

For this investigation TMP process was chosen for partly since it posses some advantages over other mechanical pulps, despite its relatively high energy consumption if compared with many other mechanical pulps. Due to its high long-fiber content, TMP has good strength properties, especially high tear strength. Therefore the extra cost of energy can be largely offset by increasing the replacement of more expensive chemical pulp fibers in a given paper grade. Although the obtainable optical properties are usually better from groundwood-based pulping processes, TMP offers the best combination of strength properties and light scattering power, for a large variety of wood-containing paper grades (Honkasalo and Ebeling 1981, Höglund and Wilhelmsson 1993). For instance, it is possible to manufacture newsprint from 100 % TMP furnish. Thermomechanical pulping process is also a very flexible process. Namely, refining of wood chips, which is usually carried out in two stages, allows the use of small amount of pulping chemicals in the form of chip-treatment prior to refining, pulp inter-stage or post-treatment. In doing so, special pulp products with improved properties can be tailored, such as chemi-thermomechanical pulp for tissue papers. TMP allows also the use of various post-treatments, such as rejects and long-fiber refining to modify pulp properties. Furthermore, the main limitation of processes basing on stone grinding (SWG, PGW, PGW-S), is seen in their incapability to utilize other wood than only roundwood bolts. One of the benefits of the thermomechanical pulping process is its capability of accepting not only pulpwood chips but also forest chips, sawmill wastes such as slabwood chips, shavings, and sawdust (Axelsson and Simonson 1983). However, to get a product of optimum quality, it is also necessary to have access to the best type of wood for a certain application (Höglund and Wilhelmsson 1993). This seems likely to be of special importance in the years to come, when the quality demanded of the high yield pulps certainly will increase considerably. One reason for this is that recycled fibers are now succesfully introduced in most paper qualities.

In order to obtain maximum paper quality, thermomechanical pulp, used for high-quality wood-containing publication papers, such as LWC-, newsprint and SC-papers, should have (Harris 1993):

1. Adequate strength properties to provide good sheet consolidation and to enable the paper to withstand calendering, handling, and good press room runnability.
2. No shive, undeveloped long fiber, chop or minishive.
3. Sufficient fines and middle fraction for good formation, high smoothness, low porosity, and high opacity (high light scattering power).
4. Low fiber coarseness for enhanced opacity, smoothness, and formation.
5. Brightness to meet requirements.
6. Sufficent proportion of long fibers, that are well developed and consistent with acceptable surface quality, in order to minimize the requirement for chemical reinforcing pulp and thereby minimize the production cost.

1.3 Concept of Wood Quality

Each of the many diverse forest products available today is most efficently produced from a particular type of wood or mixture of woods having specific characteristics. The need for the most suitable and uniform raw material for each product category is paramount, and not typical only to forest products industries. In fact, it is not possible to have wood with qualities best suited for every final product, but it is feasible to develop or select wood desirable for broad product categories such as newsprint, tissue paper and board. There are a few ways to accomplish desired wood raw material properties for a certain process or product, at least in theory:

1. Tree improvement programs
2. Silvicultural means
3. Selection and segregation of existing wood supply

Since a process or a product can come to the end of its life cycle in a relative short time, or at least within a few decades, tree improvement programs which aim to develop the genetics of a strain towards a highly specific end-use, are without practical justification. However, encouraging results have already been achieved with such programs in tropical areas, where the rotation time of a conifer can be as short as 20–25 years. Due to the above fact, a wood converter has two principal ways still available in the short and medium long term, if wood with specific wood properties is to be directed to a specific end-product. Namely, the first one of these means is the silvicultural practise and its effect on wood properties. The problem with this is, supposing that these effects are known and the desired wood properties have been identified, which, in most cases is questionable, its very limited influence, at least on the wood fiber properties (Zobel and Buijtenen, van 1989). The second, and the only effective way to directly affect the incoming wood flow and its quality, is to select and segregate assortments from existing wood supply according to the known average variation patterns which the trees naturally exhibit. Knowing the key wood properties needed for a specific product, as well as the variation that occurs in these properties in a specific geographical area or a raw material source, is naturally an important prerequisite for the operation. In this investigation, both are studied.

In pulp and papermaking, it has always been tempting to blame the wood for off-specification quality when no apparent reason can be traced. Poor wood quality and variation in it is often discussed in association of disturbances in products or production. However, the term "wood quality" is a purely arbitrary term used to describe the overall suitability of a particular wood source for a specific end-use. As applied to pulp or paper, the concept of wood quality means that wood deemed of excellent quality for one type of product may be of inferior quality or even unacceptable for use in another application, and vice versa. In literature and pulp and papermaking textbooks, several classifications are found of wood quality factors that affect pulp quality. For instance one of these is done by Bierman (1993) in his textbook of wood and fiber fundamentals. According to him, important pulping variables of wood and wood chips are: wood moisture content, specific gravity, wood physical strength, bark content, chemical composition, length of storage, amount of decay, extractives content, chip dimensions and wood species.

Few investigators have studied also the significance of basic wood quality factors in terms of mechanical pulping, among them deMontmorency 1962, 1964, 1965, McMillin 1968a,b, Giertz 1977, Brill 1985, Hartler 1985, Corson 1991, Höglund and Wilhelmsson 1993. For instance Brill (1985), found the important chip quality factors to be, with a special reference to TMP: chip size distribution, purity from unwanted wood species, cleanliness from bark, cleanliness from foreign organic and inorganic matter, wood density, fiber dimensions, defects caused by storage or decease, moisture. Perhaps the most complete listing of wood quality factors, with an emphasis also to mechanical pulping, has been made by Pulkki (1990, 1991). While summarizing the work of others, he found the following wood raw material qualities and characteristics to generally effect pulp yields and quality:

- basic density
- extent of decay
- fiber morphology
- moisture content
- chip size distribution
- branch and knotwood
- inner and outer bark
- sapwood and heartwood
- mature and juvenile wood
- chemical composition of wood
- wood extractives
- earlywood and latewood
- amount of impurities, such as sand

Occasionally, the occurrence of compression wood, and wood color (or whiteness) is found to have importance, and should be added to the listing. Some of the above mentioned factors are related to wood anatomy and structure, like fiber morphology, some of them are purely technical, like storage and chip dimensions, and some are biological like decay by fungi. However, most of these classifications tend to have only general importance. Most often they are made for all kinds of pulping processes, and not for a specific wood species, pulping process or paper product. Moreover, mainly for technical reasons, wood quality classification refers often to the properties of wood chips. The uniformity and quality of chips are of premium importance in TMP manufacture, though. Unfortunately, variation in important wood properties such as fiber length cannot be effectively controlled, if there is no data from the kind of wood and its origin entering the process at a given moment (Mannström 1977, Paulapuro et al. 1983).

Many of the above wood characteristics are interrelated and can vary greatly between species. Variation of the important wood properties, such as basic density, tracheid dimensions, latewood content or proportion of heartwood, occurs not only between different species, but most remarkably within a stem, between the stems and forest stands. According to Zobel and Buijtenen, van (1989), there are several patterns of variability within trees that are of importance. They are listed as follows:

- variation within a annual increment
- variation from the pith to the cambium
- variation with different heights of the tree

Within-tree variability can be very large. As stated by Larson (1966), "more variability in wood characteristics exists within a single tree than averagely among trees growing on the same site or between trees growing on different sites. These patterns must be understood; they are always present and are hard to eliminate." Variation in wood properties between different localities or betweem trees from the same locality can be attributed to both genetical and environmental factors. It commonly known, that the pulping properties of different parts of a tree trunk are not the same. At pulp mills these are normally being pulped as a whole. Only a small number of world's pulp mills segregate their raw material by average wood density or some other wood variable, except by species and yet they are receiving wood of different origins and pulping potential. Such assortments are for instance sawmill chips, topwood, thinnings wood and logs from old-growth forests.

Although chip configuration and wood storage, in addition to these factors mentioned above, can both affect dramatically the quality of raw material and obtained TMP, they are not considered as a wood quality factors here, since they are more or less technical parameters. Moreover, storage by itself does not effect wood quality, it just gives the time required for other factors to affect it (McGovern 1979, Kukkonen and Niiranen 1983). The different classes of damage/effects which occur during storage can be classified as:

1. Mechanical damage; drying, dirt (i.e. sand and soil), soot and debris, gathered on chip piles.
2. Biological effects; fungi, insects, bacteria
3. Chemical effects; extractives reactions, damage by bark tannins

Generally, the effects of storage are negative on wood and mechanical pulp quality. Loss of wood substance; for chip storage about 1 % per month and roundwood storage about 4–6 % after 1 year storage (Parham 1983b). This result naturally reduced pulp yields. Pulp strength properties are also expected to be poorer if decayed wood is used in mechanical pulping. The reduction of 10–15 units (% ISO) of pulp brightness is common after 4–6 months storage (Nyblom 1979).

Mechanical pulp quality and specific energy requirements appear to depend on different morphological features when the comparison is made between different tree species than when the comparison is wood variation within a species. For example, within a species, high density variants generally give better pulp quality, where on average, low density varieties are preferred when evaluating pulping potential among species. The sensitivity of mechanical pulping processes to wood species and wood density has forced them to exert significantly more control over the wood supply than the average kraft mill (Rudie et al. 1993).

However, it is obvious that the density of wood is generally a poor pulp quality indicator in coniferous pulpwood, since a change in it can result either from a change in the average tracheid diameter or the thickness of cell walls, these properties being most often independent from each others. To the present knowledge, from all wood properties, the morphological wood properties are generally considered to be most important factors determining mechanical pulp and paper quality (see e.g. Giertz 1977, Tay and Manchaster 1982, Jackson et al. 1983, Hartler 1985, Kibblewhite 1981 etc.).

According to Parham (1983), modern pulping processes can impart a variety of both chemical and physical changes to naturally variable plant fibers. However, it is often the original physical attributes of these fibers that largely determine their suitability for further processing and the ultimate quality of finished "paper". Fiber morphology – shape and size – and fiber wall architecture directly influence fiber flexibility, plasticity (deformability), and resistance to mechanical processing, and thereby indirectly influence the development of interfiber bonding and other physical properties of the end-product. Thus, while specific fiber chemistry may be deemed essential for certain pulps, the physical size and shape of the pulp particles appear to outweight chemical characteristics of the pulp fractions in predicting properties of the mechanical pulp (Veal and Jackson 1985).

1.4 Objective, Scope and Outline of the Study

The objective of the theoretical part is to analytically find out the impacts and relevance of the above chosen wood quality factors in terms in thermomechanical pulping and related paper end-products. This is carried out by critical examination of the literature. The results of the study can be then used as planning and prediction purposes in both forest industries and commercial forestry. The objectives of theoretical study can be summarised as follows:

1. Defining the wood quality factors and their occurrence in Finnish sprucewood.
2. Determination the expected impacts of these factors on TMP, and their relative importance.
3. Segregation of such pulpwood assortments, of which pulping potential may deviate significantly due to the wood factors.
4. Forming hypotheses of obtainable relative TMP properties, when these assortments are pulped separately.

Since the task is to determine the potential of Norway spruce as a fiber furnish in thermomechanical pulping, the chosen wood properties are covered as detail as possible, sometimes irrespective to their relevance in TMP, because many of their impacts are not necessarily known beforehand. The idea is to give a full coverage of the subject in order to describe them so that they will be familiar to the reader as they are encountered in discussions in later chapters, i.e. the empirical part (Chapter 3). This full treatment includes theoretical definitions of the property, its variation in Norway spruce and reasons for this, and finally, the influence of this property on TMP quality and manufacture is discussed basing on available literature. Comparisons between Norway spruce and another important pulpwood species grown in Finland, the Scots pine (*Pinus sylvestris*) cannot be avoided, which fact fits well to the purpose. This holds also to other commercial coniferous pulpwoods. Moreover, since many wood properties are in conflict in various paper products, it is necessary to discuss generally the main end-uses of TMP, that is, wood containing publication papers like newsprint, LWC- and SC-papers. Furthermore, it was necessary to use the other mechanical pulping processes, such as SGW and PGW, and sometimes chemical pulping processes, as a reference, when defining the pulping potential of Norway spruce. Summarizing all of the above, the purpose of the theoretical part of the study is to give a comprehensive view of *Picea abies* wood characteristics as a raw material for high-quality fiber products.

It is true that the variation in many of the wood properties to be studied can be independent from each others. However, in softwoods there is a certain interdependence, at least between some of the properties (Zobel and Buijtenen, van 1989). For this reason, determining the influence of each single wood property can be difficult, and rarely serves the purpose in practice (Paulapuro et al. 1983). Partly because of the heterogenous nature of wood, and partly due to the fact that mechanical pulps are not only long fibers, but consist also largely of finer particles, the mechanical pulping industry has not been able to develop a comprehensive, general model relating wood, pulp, and paper properties (Kurdin 1981, Corson 1991).

It is highly possible, that relevant wood quality factors affecting the TMP could be reduced fewer in number and simplified. This will be examined in the empirical study. Namely, as a result of the theoretical investigation, suitable Norway spruce pulpwood assortments will be formed. The effect of each assortment, with respect to single wood properties, on the manufacture of newsgrade TMP will be studied in a mill-scale thermomechanical pulping trial (Chapter 3). The objectives of empirical study are briefly summarized as follows:

1. To pulp separately the spruce assortments, selected in the theoretical study, in commercial scale at constant process conditions.
2. To test the hypotheses formed in the theoretical study in terms of obtainable TMP characteristics from different wood sources.
3. To rationalize the effects of wood variables on the quality and properties of TMP.

It should be borne in mind, that mill-scale studies of scientific interest and this size have not been performed, where TMP is manufactured from Norway spruce, and the pulp properties then being attributed to quantified wood properties. Several laboratory or pilot scale studies, though, have been made (see e.g. Hatton and Cook 1990, Corson 1991, Braaten et al. 1993) for other pulp types, other wood species or to study relationships between some single wood and pulp property. However, as it is known, these experiences are often critisized since the results obtained from trials made in laboratory or pilot scale can be far from reality, and sometimes give even erroneous data, especially, when a process such as TMP manufacture is in question. The full commercial scale mill refining enables the accurate simulation of the processes involved, as well as the wood source used. This ensures that industry may use the results with confidence. Concurrently, some flexibility could be lost in the design of an experiment (Corson 1991).

2 The Wood and Fiber Properties of Norway Spruce and Their Significance in Thermomechanical Pulping

2.1. Overview

2.1.1 General

As outlined in the preceding sections, the purpose of this study is to establish the wood and fiber characteristics in Norway spruce in terms of thermomechanical pulping and related paper end-products. In addition to knowing about wood properties, it is of greatest importance to understand what happens to wood in thermomechanical pulping. Therefore, the process itself and involved mechanisms are shortly introduced here prior to analysis of the wood and fiber characteristics. Although there is a strong reference to Norway spruce and TMP process, a secondary purpose of the theoretical study is also to serve as a "wood quality monograph" in the field of softwood mechanical pulping for various users, among them pulp and paper mill engineers, foresters, and students in related areas. The theoretical study, basing on literature, proceeds according to the framework showed in Figure 1.

As the first task, a chosen wood or fiber property will be defined and described thoroughly, starting from its physiological origin in a living coniferous tree. This is highly important, since it is the base for all the properties and variation associated with a given wood quality factor. It should be mentioned that the wood and fiber characteristics studied here are by no means uniform concepts, but some of them are mostly physical (e.g. basic density, moisture), some of them anatomical (e.g. fiber dimensions, knotwood), and some of them mainly chemical in nature (wood extractives). Furthermore, quite many wood properties are interrelated, which fact definitely makes this mission difficult.

Second task is to determine the occurrence of each wood and fiber characteristics in Finland-grown Norway spruce. This refers to average content or measure of such property, and finally its variation. It is generally known that the average fiber length, for instance, deviates between different wood species, but also dramatically within a single tree, thus, exerting a possible impact on TMP. The most important pattern of variation in conifers is the one occurring in radial direction of the stem, associated with wood age. Also environmental factors are known to affect the obtained wood properties. The above facts, in turn, set base for a possible segregation of various pulpwood assortments to be pulped separately.

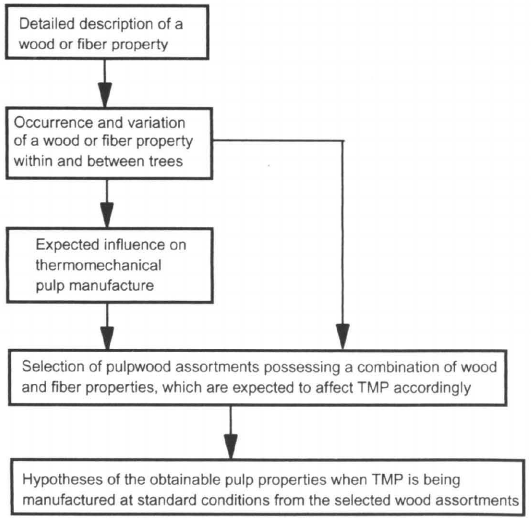


Figure 1. Framework (outline) of the theoretical part of the study.

Thirdly, the influence of each wood factor on TMP is being defined. It is obvious that quantification of these impacts can be in most cases rather difficult, since the available literature references, being in many cases rather contradicting, deal largely with other wood species or pulping processes. Moreover, as pointed out earlier, many wood properties are interrelated. Sections dealing with each wood or fiber property are arranged so that the last section is always a conclusive summary. As a result of the whole theoretical study, the wood quality factors will be listed in a matrix showing the presumed effects and importance of eact factor in terms of spruce TMP.

Finally, with respect to variation in wood and fiber properties in Finland-grown Norway spruce and the expected quality impacts on TMP caused by single wood properties or a combination of these properties, formation of relevant pulpwood assortments will be suggested. In practice, such assortments can be derived using wood originating from different age classes, site types, or wood from different parts of a stem. When the purpose is to obtain thermomechanical pulp with specific quality characteristics or to minimize unnecessary variation in pulp quality, these assortments should be pulped separately. The above gives naturally rise to an empirical study, where these concepts are to be operationalized. Prior to the empirical study, in turn, it is necessary to predict the expected average wood and fiber properties in each assortment, as well as hypothetically predict the obtained TMP properties based on the theoretical study (see Section 2.11). Moreover, as a prerequisite for the empirical pulping study, pulp quality comparisons must be made using constant process conditions to manufacture TMP of similar grade from each wood assortment.

2.1.2 Wood Quality Factors

There are several wood properties that could be discussed in terms of the wood and pulping properties of Norway spruce and its suitability for thermomechanical pulping. However, for this study, the selection of relevant wood variables is based steadily on the literature mentioned in the introductory chapter. Some of these properties were already discussed briefly earlier (Section 1.3), but the properties which are considered to be most important, will be dealt with in greater depth and detail in this theoretical study. It should be mentioned that, with the exception of a small number of rather limited investigations (see e.g. Eriksen et al. 1977, Giertz 1977, Abadie-Maumert et al. 1985, Brill 1985, Hartler 1985, Sundblad 1992, Höglund and Wilhelmsson 1993, Braaten et al. 1993) there are, in fact, no consistent data where the special reference is both Norway spruce and TMP. Furthermore, since no comprehensive study has been made on the subject, this chapter (Chapter 2) is aimed to be a partial contribution to this field of interest.

It is intuitively obvious that various wood properties can be significant only for some particular pulping process and paper grade, or, they can have more pronounced importance only when associated with a certain wood species. Moreover, some properties can exert an effect on TMP, when their occurrence exceeds a certain limit etc. Therefore, it is imperative to treat these wood factors with similar, thorough manner to find out the quality impact and preferably the magnitude of this impact. It may also become clear that the influence of a certain Norway spruce wood property on TMP can be practically zero or is rather difficult to quantify, even though this is not necessarily the case with some other wood species or pulping process. The above can be attributed to great variability of wood properties within and between the wood species, or basic differencies in pulping mechanisms.

For this investigation, the properties of Norway spruce that are presumed to have influence on the production and properties of TMP, and manufactured paper end-products are:

1. wood basic density
2. moisture content
3. tracheid length
4. tracheid diameter and cell wall thickness
5. latewood content
6. juvenile wood content
7. heartwood content
8. knotwood content
9. extractives content

They are not listed in any relative order, but with respect to variation that occurs in Norway spruce and generally in softwoods, all of these must have some influence. A wood quality factor which has been intentionally disregarded, is *compression wood*, of which merely detrimental effects on mechanical pulps are widely known (see e.g. Watson and Dadswell 1957, Pillow et al. 1959). There are few reasons for this. Namely, the incidence of compression wood in spruce pulpwood can vary from negligible to unpreferable amounts (Timell 1986), and its occurrence, however, is not mainly specific for any pulpwood assortment or stem part, but largely a local and random phenomenon. In the light of this, it would be not justified to reserve too much space for this subject. Furthermore, despite that *bark content*, *chip configuration*, and *wood storage*, in addition to these factors listed above, can all affect dramatically the quality of raw material and obtained TMP, they are not considered as a wood quality factors here, since they are more or less technical parameters. It is known that wood storage by itself does not affect wood quality, it just gives the time required for other factors to affect it.

2.1.3 Thermomechanical Pulping Process

Thermomechanical pulping process is capable of producing pulp from a wide range of softwoods throughout the world and the unbleached pulp is suitable for use as the major furnish component in newsprint and associated grades of paper (Kurdin 1979, Jackson 1985, Nordman 1987). Many of the advantages of TMP over other mechanical pulps and pulping processes were already presented in the introductory chapter (Chapter 1.3). In this and the following section the process itself and the theory of refining wood thermomechanically are shortly introduced, in purpose to understand what happens to wood and fibers during refining, as well as what is the origin of pulp properties. Complete descriptions can be found elsewhere, that is, in various textbooks and studies published on the subject.

The TMP or thermomechanical pulping involves the comminution of heat-softened chips into individual fibers by refining (Jackson 1985, Leask 1987a). Unlike chemical pulps, the resulting TMP is composed only partially of whole fibers (30–40 %), most of the substance being broken fibers and finer particles. The process consists of the presteaming and first-stage refining at elevated temperature and pressure. There are processes with a straightforward approach that have only one stage, but most often the first stage is followed by secondary refiner, in which refining can be carried out either atmospherically or under elevated pressure. Moreover, refiner design can be of either single-disc or double-disc type, where both refiner plates rotate in opposite directions. Pulping is normally practiced according to some variant of the process outlined in Figure 2, where a two-stage pressurized TMP system with heat recovery is schematically shown.

When roundwood is used as a raw material source, the following wood-handling operations involved in the process must always be carried out prior to pulping: pulpwood reclaim, debarking, chipping, chip screening and chip washing. It is essential that all the chips, either produced at the mill or purhased from sawmills, must be both screened and washed (Hartler 1977, Leask 1987b). Stored wood, in any form, should be avoided, and only fresh wood should be used, if high-quality TMP is the primary objective.

The accepted, washed and dewatered chips go to an atmospherical steaming bin for about 15–25 minutes, where exhaust steam from the refiner system is introduced in purpose to initiate the thermal softening (Goring 1963) and drive off some of the entrained air which is detrimental for any heat recovery system. The chips are then fed through a rotary valve or some other means into the preheater where steaming, for 2 to 5 minutes, is done at an elevated pressure (160–200 kPa) and temperature (120–130°C), whereafter they are conveyed into primary refiners through a plug screw feeder. Refining consistency is 30–40 % in the first-stage, and somewhat lower in the second-stage. After secondary refiner, the refined pulp is diluted to a low consistency and is being agitated at a 85 to 90°C for approximately 30 minutes in a latency chest. This allows the fibers relax and straighten before they are screened in purpose to remove fiber bundles (or shives). The power split between the two refining stages is approximately 50/50, the total specific energy consumption being dependent upon the type of raw material being used and the wood species. Heat is usually recovered from both stages. In addition to 1-stage and 2-stage refining, rejects are in many cases refined in separate refiners (see e.g. Mannström 1977, Paulapuro et al. 1983, Leask 1987b).

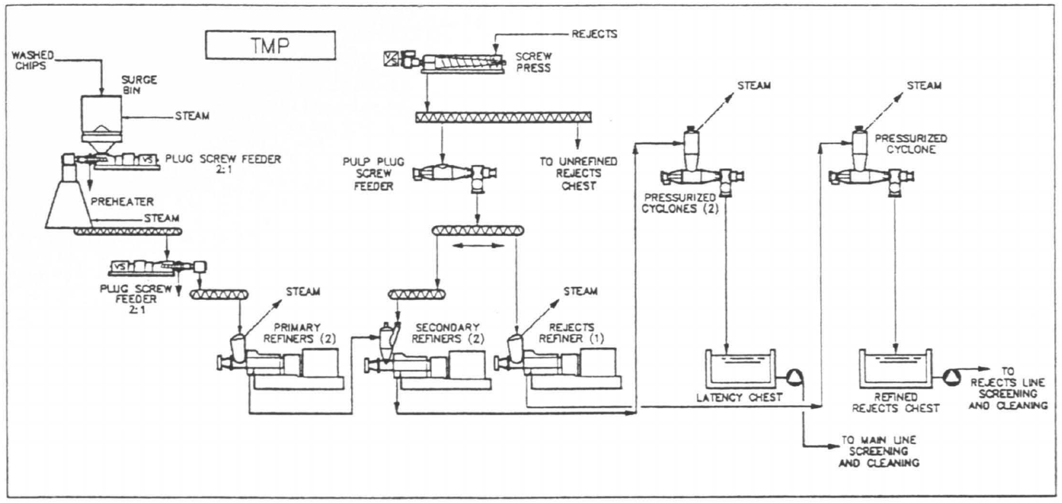


Figure 2. A schematic diagram of softwood two-stage pressurized mainline TMP system with heat recovery (Barbe et al. 1993).

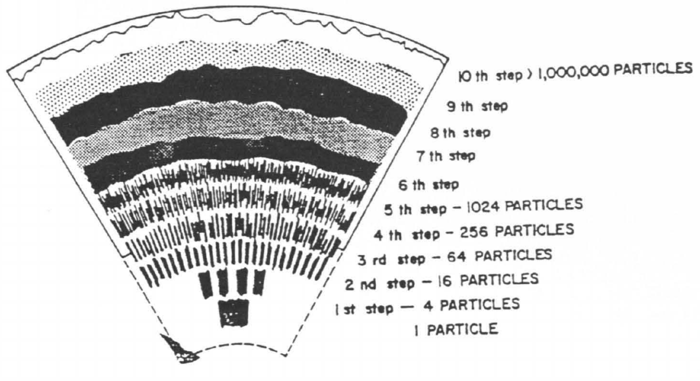
2.1.4 Theory and Mechanics of Thermomechanical Pulping

The purpose of mechanical pulping is that of detaching the fibers from the wood material, and converting them into papermaking fibers which are capable of forming interfiber bonds. Schematically mechanical pulping can be divided into three processes:

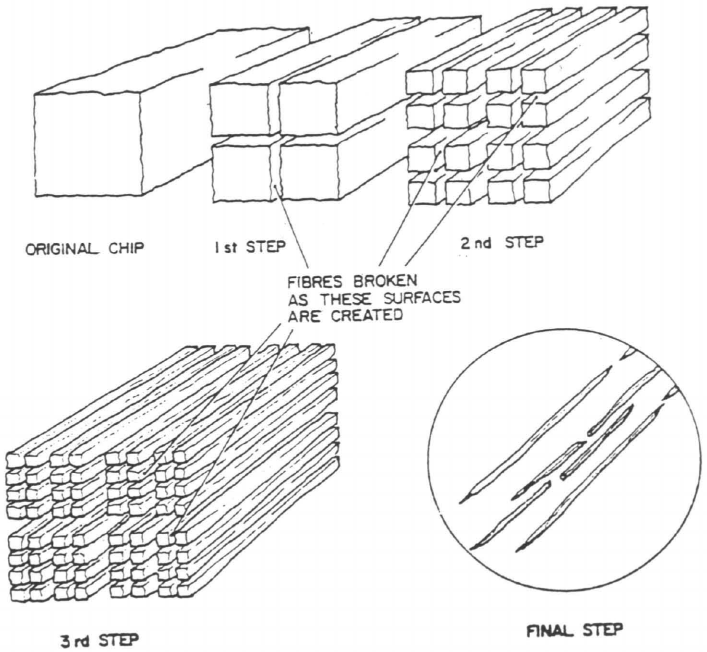
1. Separation of fibers from wood matrix
2. Development of fiber bonding ability
3. Creation of fines material

The first work of refiner mechanical pulping (RMP) for newsprint production was reported in the early 1950's. Before this, mechanical pulping was based only on wood grinding. Interest in refiner mechanical pulping grew slowly until the development of thermomechanical pulping (TMP) which started in 1968. In fact, as early as 1932 wood were defiberized thermomechanically with the Defibrator-method for structural boards (Asplund 1953). However, commercial interest has grown significantly since the early 1970's and this process represents today a well-established technology (Leask 1981).

As being obvious from the foregoing, thermomechanical pulping process is modified wood refining. In refining, wood chips are first fed into the refiner eye of primary refiner. Some dilution water is always added in between the refiner plates to facilitate wood defiberization and subsequent handling of the fiber suspension. Thus, considerable recirculation of steam and pulp takes place in the inner section of the refining zone (Atack 1980). In refiner pulps, separation of fibers takes place in the primary stage, where chips are comminuted into finer particles and finally into fibers. According to Atack et al. (1983), the chips have been observed to break down in the middle section, or "breaker zone" of the refiner plates. It was May (1973), who firstly proposed a comprehensive chip comminution theory, where a chip particle gradually breaks down into smaller particles (see Fig. 3). As chips are subjected to repeated compression and decompression, the amount of these particles increase exponentially from the inner zone of a plate onto the outermost refining zones, until wood is defiberized into single fibers. In this latter



Model refining zone.



Model of chip disintegration.

Figure 3. Break down of wood matrix in a disc refiner according to May (1973).

zone, the plate pattern is very fine, the plate gap being so narrow that there is room for only a few fibers between the bars of plates at any given time (Pearson 1983). It is well known, that only a minor portion of refining energy is consumed for fiber separation, the bulk of this energy being used for developing the bonding properties of fibers and creation of fines material, which takes place throughout the pulping (Kurdin 1979, Jackson 1985, Karnis 1994).

The concept that refining consists of two mechanisms – a compressive mechanism to partially collapse the lumen and a second mechanism which involves rolling of the fiber while it is compressed

– was proposed by Pearson et al. (1978). Disc refining is often referred to as longitudinal wood grinding. This is because the fibers in the refining zone have been observed to be mostly tangentially oriented, which is the position causing the least resistance. Due to the above, the stresses caused by the refiner disc bars are directed mainly along the fiber length (Atack 1980, Atack et al. 1983). Moreover, this "longitudinal grinding" requires substantially, more energy than stone grinding. When newsgrade pulp (80–100 ml CSF) is produced from sprucewood, the specific energy consumption of SGW is about 1200 kWh/t, for RMP about 1600 kWh/t, and that for TMP about 1900 kWh/t and more (Paulapuro et al. 1983, Leask 1987b). It is therefore intuitively clear from different specific energy requirements and pulp characteristics between SGW and TMP that the mechanisms involved with wood grinding are largely different from those involved with chips refining.

Thermomechanical pulping was further developed from refiner mechanical pulping (RMP) as it was found that thermal softening of the lignin prior to refining resulted in a larger proportion of long fibers and less shives, and therefore stronger pulps. All cell wall mâjor chemical constituents, that is, cellulose, hemicelluloses, and lignin, begin to soften at different temperatures (Fengel and Wegener 1989). Hemicelluloses, the principal intercellular substance between the microfibrils, begin to soften at 50–60°C, whereas the lignin which connects the fiber walls to each other softens at 90–100°C. Cellulose, which imparts its axial strength to the fiber remains unchanged up to 230–240°C (Goring 1963). The above values are for wood in wet state (above fiber saturation point), and lignin in dry wood must be heated to much higher temperatures, from 130 to 190°C, before it becomes thermoplastic. Work by Koran (1966, 1968) has shown that the type of fiber separaration is dependent upon system temperature. In RMP manufacture the fiber separation occurs mainly along secondary cell wall (mainly S_1-layer), whereas in the case of TMP, the thermal softening of wood matrix followed by refining, the fiber separation can be changed from secondary wall layers to primary wall. The above is assumed to occur at about 130°C with a loading frequency at around 20000 kHz (Becker et al. 1977). Elevated temperature is allowed because the chips preheater and refining is pressurized. It is true that if temperatures of as high as 170°C are used, fibers are detached along the lignin-rich middle lamella, but such fibers are dark, covered with lignin and have very poor bonding properties. In thermomechanical pulping, temperatures somewhat below 130°C are normally used, as proved by many years of mill practice (Mannström 1977, Leask 1987).

In fact, TMP process largely bases on findings by Höglund and Becker, and their coworkers (see e.g. Höglund et al. 1976, Becker et al. 1977). They studied the mechanics of defiberizing in Norway spruce concluding that there is an optimum temperature where maximum fiber length and flexibility is being reached. This temperature is dependent not only on the wood species and moisture but to a great extent on the frequency of the mechanical work done in the refiner. Furthermore, according to their theory, the temperature should increase along the radius towards the periphery of the refiner disc, which is not always the case in practice. Salmén et al. (1985), who simulated fiber defibration in refining process using Norway spruce in their wood fatique studies tests, further completed the previous theories. They found a strong dependence of the treatment temperature and frequency on the structural changes of wood, this behavior being similar to amorphous polymer materials. Namely, the structural breakdown of wood is favoured by an increase in temperature and a reduction in the treatment frequency. According to their theory, the pre-steaming of chips and fiber separation stage should be performed at a lower temperature than that at which the flexibilization and development of the fibers is promoted, if fibers with good bonding properties are to be obtained.

According to Leask (1981), the refining itself is a very complex action involving many variables including wood species, internal moisture content, refiner plate pattern, refining temperature, frequency, refining consistency, steam generation, steam flow, motor load etc, and their effects on refining must be understood better. It is true that with the development of thermomechanical pulping process, the energy needed to separate fibers did decrease (Kurdin 1979, Hattula and Mannström 1981). Unfortunately this is only a small portion of total power consumption and no

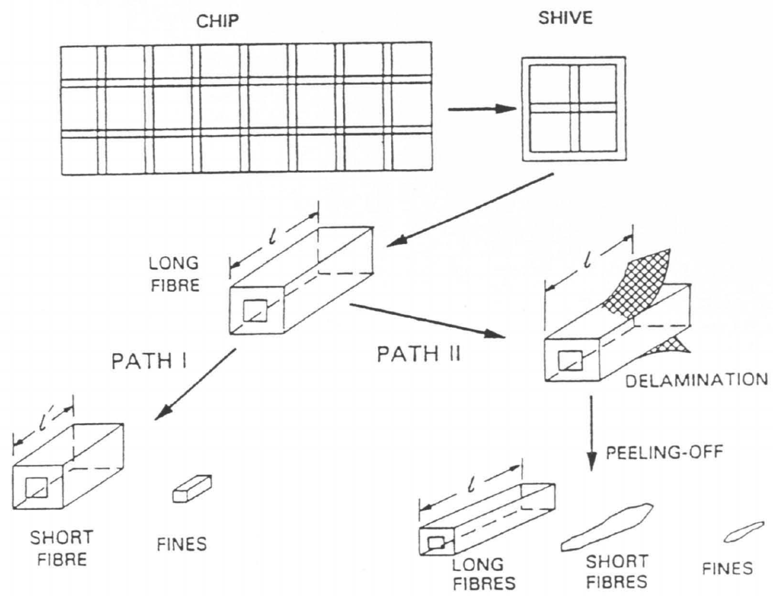


Figure 4. Schematically shown mechanism of fiber development according to Karnis (1993). In the fiber separation stage chips are reduced to shive and long intact fibers. In the comminution theory (path I) part of the long fibers are broken.

savings in energy consumption was achieved. Obviously more work is needed in fundamental concepts of refining, since no solution is still found to the high energy costs associated with the production of TMP.

A lot of lately accomplished studies have shown, that the primary stage refining is largely responsible for establishing the characteristic properties of the pulp, including the average fiber length, and that secondary refining only has a marginal influence in this respect (Stationwala et al. 1991, Heikkurinen et al. 1991, Karnis 1993). Only very recently, Karnis (1994) has proposed a mechanism for fiber development in refiner pulping, including TMP. Namely, he proved that pulp fiber coarseness of the long fiber fractions decreased consistently during pulping, along with applied refining energy. Therefore, fibers are not primarily broken into shorter particles in refining, but the development occurs through delamination and stripping away of material from the cell wall as more energy is added (see Figure 4). According to him, the short fiber fraction and and fines originate mainly from the middle lamella and cell wall material of longer fibers. The above gradual peeling off the fiber layers through fibrillation is partially confirmed by Heikkurinen and Hattula (1992), who characterized the nature of fines material during thermomechanical refining. They found that the lignin content decreased and cellulose content in fines increased along with applied refining energy, corresponding well with their relative proportion in various cell wall layers.

2.2 Wood Basic Density

The basic density of wood is perhaps its single most important physical gross measurement since it can offer useful means for predicting such end use characteristics of wood as strength, stiffness, hardness, and papermaking attributes. Both terms wood specific gravity and basic density are used to express how much wood substance is present in a given volume of wood. However, the latter term has been commonly adapted by wood scientists and technologists, because of its practical utility. It is defined as to the ratio of dry weight per unit volume of green (swollen) wood (Haygreen and Bowyer 1989). Variation in xylem basic density is mainly caused by variations in the proportion of cell wall material, the density of which is slightly over 1500 kg/m^3 in oven-dry condition (Kellogg and Wangaard 1969). In fact, wood basic density is not a single characteristics but is determined by several characteristics of wood such as cell size and wall thickness, the ratio of earlywood to latewood, the amount of ray cells, and several other factors (Zobel and Buijtenen, van 1989). Thus, in the light of the above, the use of basic density to predict wood fiber morphology can be applied only in limited conditions.

According to several investigations (see e.g. Nylinder and Hägglund 1954, Tamminen 1964, Ericson 1966, Hakkila 1966, 1968 and 1979, Olesen 1976 and 1977) the latewood percentage is the factor with which the basic density of Norway spruce is most strongly correlated, when the juvenile wood zone (innermost 15–25 rings) is excluded. A typical average basic density of Norway spruce latewood is above 600 kg/m^3, whereas that of earlywood is usually less than 300 kg/m^3, these densities being quite independent from ring number (Johansson 1940, Olesen 1976). Moreover, numerous investigators have concluded that there is a strong negative correlation between the basic density and ring width, i.e. growth rate (Klem 1934, Nylinder 1953, Ericson 1960, Bernhart 1964, Hakkila 1966, Olesen 1973). However, it should be pointed out that the above correlation holds to limited ring widths (Hakkila 1966) and is not linear but depends on ring age (Olesen 1976 and 1977).

2.2.1 Variation in Wood Basic Density

The basic density of Norway spruce has been studied by numerous scientists in the present century and even earlier. For Finland-grown spruce stems, Hakkila (1979) has determined the average basic density in spruce to be 387 kg/m^3 with stem-to-stem standard deviation of 30.2 kg/m^3. In this comprehensive survey, the material represented the total growing stock of Finland's forests in different parts of the country. Depending on the method of measurement and from which part of the stem the sample is taken, values ranging from 328 to 420 kg/m^3, has been measured for average wood basic density of spruce grown in Finland (see e.g. Hakkila 1966, 1968 and 1970, Hakkila and Uusvaara 1968, Velling 1976). Unlike in Scots pine, the average basic density of Norway spruce has been observed to increase generally from southern Finland towards the north. The average south-to-north variation can be considered very moderate. Namely, according to Hakkila (1968), the average basic density of spruce pulpwood increased from 379 to 387 kg/m^3 with increasing latitude, from the 62th parallel to the 66th parallel. Since also contradictory results have been obtained with spruce, genetic reasons, in addition to growth conditions, may explain this geographical variation (Wegelius 1946, Hakkila 1968 and 1979). In general, Norway spruce can be categorized as a "light" wood species according to Panshin and deZeeuw's (1980) classification.

Within a coniferous stem, the variation of wood basic density typically occur in both *radial* and *longitudinal directions*. Changes occuring from the pith toward the bark, at a given stem height, have often relationship to age and rate of growth. Namely, in all those conifers, among them Norway spruce, in which the basic density show an increase from pith toward the cambium, the higher stem age means higher average wood basic density (see Table 1 and Figure 5). In fact, stem age is the single most important factor explaining basic density variation between spruce stems (Hakkila 1966). High average basic density in old spruce trees, and especially in outer parts of the stem, results inevitably from the fact that conifers tend to form narrower growth rings towards the end of their life cycle, while, at the same time, the width of latewood remains practically constant and its density rather increases than decreases

Table 1. Basic density of Finland-grown Norway spruce on different forest site types (Hakkila 1966). The site quality decreases downwards.

Forest site type	Age, years				
	25	50	75	100	125
Oxalis-Myrtillus (OMT)	356	364	372	380	...
Myrtillus (MT)	368	376	384	392	400
Vaccinium (VT)	376	383	391	299	407
Swamp	379	387	395	403	410

towards the cambium (see e.g. Hakkila 1968, Olesen 1976 and 1977).

Norway spruce shows only a modest pattern of basic density variation in radial direction, unlike in Scots pine and many pine species. Typically in spruce the difference in basic density between inner and outer wood is usually less than 25 kg/m^3, whereas in old pine trees the basic density can increase directly from pith to bark, but with decreasing speed, well over 100 kg/m^3 (Nylinder and Hägglund 1954, Tamminen 1964, Hakkila 1966). In southern yellow pines, for instance, the basic density can increase quite linearly from approximately 300 to over 500 kg/m^3 in a single stem (Megraw 1985). Contrary to the situation with the Scotch pine, the basic density of Norway spruce is found to be relatively high, approximately 450–500 kg/m^3, in the immediate vicinity of pith. After the first two to four growth rings the basic density decreases rapidly towards the cambium, but, a few annual rings later, begins again to increase towards the cambium, reaching the same or even higher values than around the pith (Tamminen 1964, Hakkila 1966, Olesen 1976, Kucera 1994). The latter case occurs in old stems. When Hakkila (1966) in his study, determined regression models for spruce wood density and ring width, he had to exclude the influence of the above mentioned innermost juvenile growth rings from the examination. High basic density values around the pith in spruce wood, has also been reported to relate, in addition to the juvenile wood phenomenon, with the existence of "mild" compression wood in this wood tissue (Larson 1969). The following figure (Fig. 5) shows the radial basic density variation at different relative heights of a spruce stem.

As being obvious from the above (Fig. 5), wood bolts (or logs) taken from different parts of a stem have different average basic densities, thus influencing on the value ratios of timber assortments. Largely because of this, the longitudinal variation in basic density has been thoroughly studied. As a general trend, majority of conifers, including all *Araucaria*, *Larix*, and *Pseudotsuga*, and almost all *Picea* species investigated tend to develop a lighter wood with increasing stem height, albeit more slowly within the living crown than below (see e.g. Timell 1986, Zobel and Buijtenen, van 1989). This is also a typical trend in two thirds of the pine species examined. In spruces, by contrast, the density of the wood first decreases until a point 1/2 to 3/4 of the total stem length, after which it begins to increase toward the top (see Figs. 5 and 6). This type of variation for Norway spruce has been reported for instance by, Tamminen (1964), Hakkila (1966, 1979) and Andersson (1983), but also somewhat contradictory results have been obtained (Nylinder and Hägglund 1954). The variation in basic density along stem height is usually no more than about 20 to 30 kg/m^3 in spruce, the highest densities found usually in butt logs.

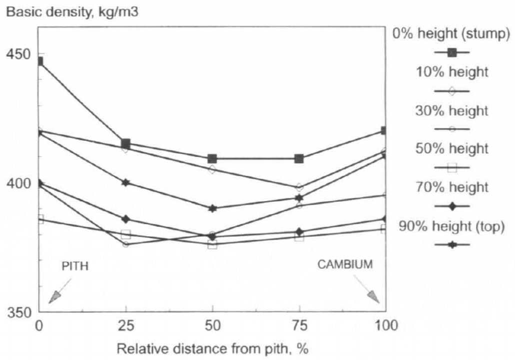


Figure 5. Variation of wood basic density in one 71-year-old sample tree (dbh 24 cm) from Tamminen's (1964) material of Sweden-grown Norway spruce.

As being clear from the foregoing, the variation of the average basic density in Norway spruce, either in radial or longitudinal direction of the stem, is rather modest, unlike that of pine species, for instance. Therefore, it seems that other forms of variation than intra-tree variation more of importance, if different wood assortments arriving a pulp mill are considered. With respect to growing environment and genotype, it is known that the stem-to-stem variation of spruce can be considerable, even from a same forest stand. For instance, Hakkila (1966) showed the average stem-to stem basic density to vary from 308 to 482 kg/m^3, in a material which was collected from geographically restricted area. As many other wood properties, basic density in Norway spruce is under strong genetic control, which largely explains the above variation (Ericson 1960). The remainder of the variation is then explained by several environmental factors, related to tree growth and growing site. However, these factors are not the main scope of this study.

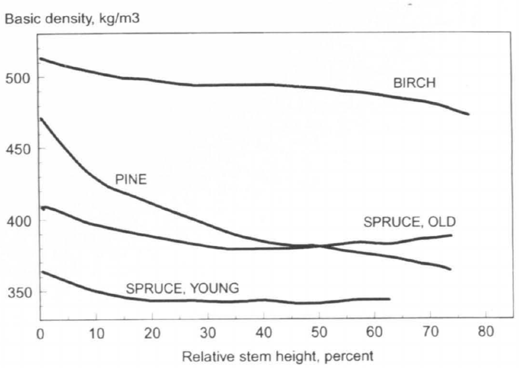


Figure 6. The variation pattern of average wood basic density in the longitudinal direction of the stem in southern Finland in *Betula pendula, Pinus sylvestris* and *Picea abies*. The ages of trees are over 80 years, except for the young spruce shown as a comparison, having the age less than 40 years. Data is based on several hundred stems (Hakkila 1966).

Nevertheless, site quality is known to have a profound effect on the basic density between Norway spruce stands. Irrespective to the effect of tree age, discussed earlier in this chapter, the basic density of softwoods is observed to be higher on poor than on good sites. Rich soil conditions contribute fast tree growth and therefore low basic density, whereas, a suppressed spruce stem of the same age on the same site grows slowly, yielding higher wood basic density (Hakkila and Uusvaara 1968, Velling 1976). The effect of site for Norway spruce basic density is shown in Table 1. Furthermore, general trend in conifers is that trees growing at close spacing produce heavy wood and open-grown trees with large crowns produce wood of relatively low density (Hakkila 1966, Kärkkäinen 1984). As stated by Zobel and Buijtenen, van (1989), regulation of growing space throughout the life of a stand is the silvicultural tool most readily available to the forester in controlling wood density.

The following figure (Fig. 7) shows the correlation between tree density and age in natural and plantation forest of Norway spruce. In this case, according to Hakkila and Uusvaara (1968), the differences in wood density between naturally and plantation forests, may be caused partly by differences in growth rate, but partly may also be caused by genetic factors.

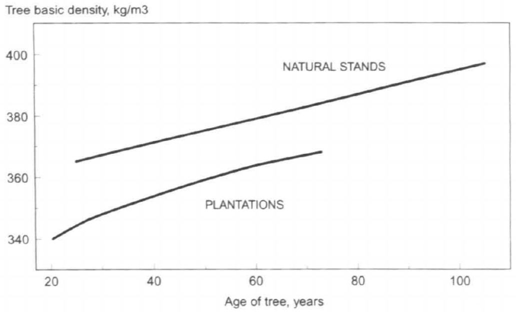


Figure 7. Correlation between tree density and age in natural and plantation forest of Norway spruce according to Hakkila and Uusvaara (1968).

2.2.2 *Influence on TMP Manufacture*

Wood is mainly bought by a unit volume to the mill. Furthermore, wood debarkers, chip silos, digesters, refiners and other process equipment can handle a certain volume of material at a given time, thus the wood density can influence the final capacity of such production line. In fact, the wood basic density directly affects the pulp yield that can obtained from a unit volume (measured in oven-dry state) of wood in a way that a unit volume of wood contains more fiber the higher the density of wood. This is the case especially with mechanical pulping, i.e. TMP and other high-yield pulps, where almost all wood substance is converted to pulp with a minimum fiber loss.

According to Parham (1983), "heavy" woods are favored in *chemical pulping*, if the capacity of pulping line must be optimized. Furthermore, higher density wood from the same species usually give stronger chemical pulp, especially in terms of tear strength, than corresponding lower density wood (see e.g. Stairs et al. 1966, Hatton and Cook 1990). In literature, there are several references involving various softwood species, generally stating that "light" wood, despite of lower yield, rather than high-density wood is preferred in *mechanical pulping* (see e.g. Dadswell and Wardrop 1959, Schafer 1961, Besley 1962, McMillin 1968a, Pearson 1984, Brill 1985, Megraw 1985, Williams 1993, Rudie et al. 1994 etc.). Traditionally, major part of the research has dealt with wood grinding process. However, in the light of available knowledge of pulping wood of different basic density, it seems that low-density softwoods such as northern spruces give stronger mechanical pulp with better optical properties and lower power consumption, than high-density species, like for instance pines and Douglas-fir. *Within a species*, higher density wood from mature wood is usually favoured in terms of pulp strength properties. It should be borne in mind that some of the indirect impacts of wood basic density on TMP, are discussed more in detail elsewhere in this study, along with approppriate wood property, such as latewood, juvenile wood, and fiber cross-sectional dimensions (Sections 2.5, 2.6 and 2.7).

According to Pearson (1983) and Kurdin (1979), rigid and thick-walled fibers that originate from high-density wood raw-material, require extra energy in refining, compared to thinner-walled fibers. This is supported by Rudie et al. (1994) and Laurent et al. (1993), who both attribute these effects to differences in latewood content and physical behavior of this wood tissue, in their fundamental refining mechanics studies made with loblolly pine (see Section 2.6). When different wood species were refinined thermomechanically, it has been shown by several investigators, among them Jossart et al. (1987), Härkönen et al. (1988) and Corson et al. (1989), that low-density northern spruce species require constantly less refining energy to reach the same freeness level, than higher density pine wood with coarser fibers. The obtained pulp strength and optical properties are also generally poorer from pines.

In terms of density variation within a single softwood species, the wood – mechanical pulp relationships are not that obvious. A fundamental finding made by Corson (1983) in *Pinus radiata* TMP, has been that juvenile wood behaves differently from mature wood in pulping, suggesting that these two wood tissues must be considered differently with respect to basic density and other wood properties (see Section 2.7). Perhaps, this is one of the reasons why actual correlation has not been found between wood basic density and pulp properties. However, in the case of mature wood refined to constant 100 ml (CSF) freeness level, higher density mature wood with a basic density of 453 kg/m^3, while consuming about 10 % more refining energy (see Fig. 32 in Chapter 2.7), gave approximately 13 % better tear index, 12 % more long fiber, but 1 % poorer light scattering coefficent, than lower density wood with 395 kg/m^3 basic density. No dramatical differences were found in tensile index, burst index or sheet apparent density.

Contrary to what has been discussed above, Corson (1991), has shown in his later extensive investigation about radiata pine wood in refiner mechanical pulping, that wood basic density, has approximately no impact on TMP quality or specific energy consumption. This led him to conclude that it is principally the properties of the fiber wall and its response to refining that determine fiber behavior and overall pulp quality, rather than the cross quality of the wood itself. Moreover, pulp properties could be best explained by wood type, that is, butt log, second log, top log, as rationalized with the existence of mature and juvenile wood. The above is partly supported by Michelic et al. (1972) with mill-scale refining a mixture of Canadian wood species *Picea mariana* and *Abies balsamea*, and Brill (1985), being the only report on the TMP refining experiments of Norway spruce of various densities.

Brill found practically no correlation between the wood density and TMP properties or energy consumption. In fact, he reported that there was a maximum level of TMP specific energy consumption in the density of about 350 kg/m^3, whereafter the energy requirement decreased rapidly with lower or higher wood densities. Similar findings, having been also remained unexplained, has been made by de Montmorency (1965) with black spuce (*Picea mariana*) RMP, but not that made from white spruce (*Picea glauca*), when he refined Canadian softwoods having various basic densities. Both of these conifers are being quite similar to Scandinavian-grown Norway spruce in terms of their wood and fiber properties. Moreover, basing on his experiments and subsequent statistical analyses, he stated that wood basic density does not appear to be a very useful criterion of the mechanical pulping characteristics of trees within a single wood species.

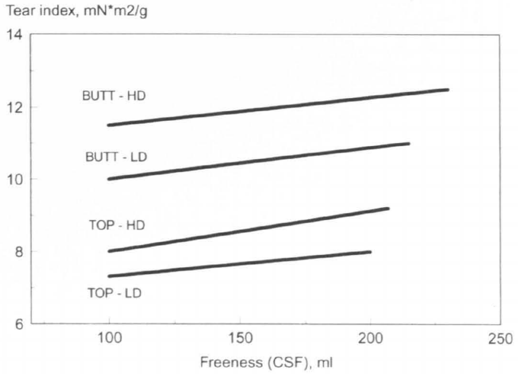


Figure 8. Tear index vs. freeness in TMP made from high (HD) and low density (LD) radiata pine (*Pinus radiata*) butt and top logs. Note, that wood from top logs are consisted of juvenile wood. (Corson 1983)

According to Brill's (1985) study, the increase of chip basic density in Norway spruce resulted in accordingly higher average TMP fiber length, and therefore improved tear strength (see Section 2.4.2). This is supported by Hatton and Cook (1990), who found relatively good positive correlation (coeff. 0.58) only between the wood density and pulp tear strength among the studied handsheet properties in RMP made from Douglas fir (*Pseudotsuga menziesii*). Evidence from elevated pulp long fiber content and tear index with increasing wood basic density, is found also by Alftan, von (1958) in Norway spruce laboratory-scale groundwood (see Table 6 in Section 2.6.2), and by Corson's (1984) studies with *Pinus radiata* refiner pulps as discussed earlier in this chapter (see also Figure 8). Furthermore, Brolin et al. 1995 studied the effect of spruce (*Picea abies*) wood from agricultural land on pulping. This wood had generally lower average basic density, ranging from 314 to 382 kg/m^3, than the reference pulpwood from forest stands in central Norway, where it varied from 350 to 414 kg/m^3. At constant tensile index level of 30 Nm/g, TMP from agricultural land had 20–35 % lower tear index, but 10–20 % higher light scattering coefficent, than the corresponding reference pulp. No savings in specific energy consumption were reported. It should be mentioned here, that the authors attributed these differences, not to be influenced by basic density, but fiber morphology and wood type, i.e. juvenile wood.

Since mechanical pulp tear strength is strongly controlled by pulp long fiber content and average fiber length, it can be suggested, basing on majority of pulping studies found, that latewood fibers or, generally, fibers with thicker cell walls originating from higher density wood could retain their length well in final pulp, which, in turn, results in good tear strength. However, since contradicting findings also exist, the above could apply only to a limited wood species or range of basic density. For instance, deMontmorency (1965) found that the proportion of long fibers and tear strength were not influenced by wood basic density, neither in groundwood nor in refiner mechanical pulps, made from *Picea glauca*, *Picea mariana* and *Abies balsamea*. Moreover, in a study by McMillin (1968a) tear strength of RMP made from *Pinus taeda*, decreased constantly by about 20 % when wood basic density increased from 450 to 500 kg/m^3. The same trends were determined for pulp tensile and burst strengths.

The effect of wood density, in addition to what has been discussed before, on other mechanical pulp strength properties, such as tensile and burst strength, is not very obvious, according to the literature discussed in this chapter. For instance, according to Hartler (1985), high density wood is poorer raw material for refining in the sense that it requires more energy and the resultant pulp at the same freeness has a lower tensile index. The relationship between wood density and tensile index of Norway spruce TMP at the same freeness level, is shown in Figure 9. Caution should be observed, because extremely high wood density values, and thus resulting poor tensile strength, may be explained by the existence of compression wood in this case. In the study of Michelic et al. (1972), when the density of black spruce-balsam fir chip mixture increased from 370 to 410 kg/m^3, the burst strength of mill-scale RMP decreased by 25 %. Unfortunately, data is missing from other important wood – pulp relationships. Furthermore, Stairs et al. (1966) have interestingly found in their study, where refiner mechanical pulp (RMP) was manufactured from fast- and slow-grown spruce (*Picea abies*) tree from the same stand, that a fast-grown tree gave somewhat (from 1 to 11 %) better pulp quality, in terms of

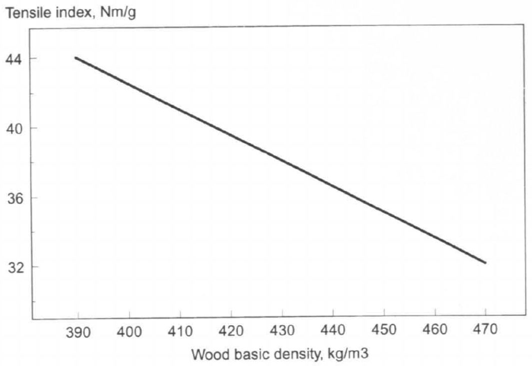


Figure 9. Effect of wood density on tensile index of spruce TMP according to Hartler (1985). All tensile index values are at 100 ml freeness (CSF) level.

pulp optical and strength properties, at the same freeness level. However, they did not succeed to show that any of the above mentioned variation in pulp properties could be caused by wood density difference between trees, and, due to the small scale of the study, definitive conclusions are not justified.

Only limited data exists of the effects of wood density on mechanical pulp optical properties. (see e.g. deMontmorency 1965, Corson 1983, Hartler 1985, Hatton and Cook 1990, Suckling 1993). Generally, low density wood is expected to produce pulp with better light scattering and brightness than high density wood, because there will be less latewood fibers, and more earlywood fibers and fines material in the resulting pulp, if same refining conditions are employed. The two latter factors contribute to good light scattering power of TMP. This is supported by Corson (1984) who found that low density Pinus radiata mature wood produced better light scattering coefficent that corresponding high density variant, when plotted either as a function of pulp freeness, specific energy consumption, sheet density or tensile index (see Fig. 32 in Section 2.7).

What has been discussed here about wood density and its rather contradicting relationships or no correlation at all with TMP properties, can be considered more or less logical, since neither the wood density nor any pulp property, such as pulp tensile strength or brightness, is a simple characteristics, but a combination of several factors. For instance, although the wood density, can be a good indicator of the type of fiber in raw material, such as percentage of latewood in Norway spruce in limited conditions, it could be presumed that the pulp's papermaking potential could be easily predicted from it. This can be the case with kraft-pulping, but in mechanical pulping processes the proportion of thick-walled latewood fibers to thinner-walled earlywood fibers do not remain approximately the same as in raw-material after wood has been pulped, but can change greatly, depending on the wood raw-material, and the degree or type of given treatment (see Section 2.6). Moreover, when the density of wood is varied, the other wood properties, such as fiber wall thickness, fiber length or lumen size, do not change proportionally with it, not even within the same wood species. Therefore, most of the effects of wood density in the manufacture of TMP, should be attributed to other wood and fiber properties, discussed elsewhere in this study.

In TMP manufacture, the most important process parameter to produce pulp of uniform quality is *refining consistency*, which is determined by the production rate of dry wood and the total water flow that enter the refiner (Miles and May 1990). The effect of consistency is universally known, not only among the pulp mill people, though it is not well documented in literature (Michelich et al. 1972, Stationwala et al. 1979, Miles 1990, Cort et al. 1992, Fournier et al. 1992, Hill and al. 1993, May 1993). Thus, there is a reason to assume that not the wood density itself, but the continuous variations in chip basic density and/or moisture content affect dramatically the quality of obtained pulp.

It is expected that *wood density variations* will result in quality variations in thermomechanical pulps for at least two reasons (Michelich et al. 1972). Firstly, since chip flow is in most cases metered by volume, wood density variations in the primary refiner feed will directly affect the mass production rate, refiner specific energy and refining zone consistency. If the refiner motor load is kept constant, pulp quality must vary accordingly. For those TMP-refiners fed at constant volume, pulp production will decrease accordingly when low density rather than high density wood is used. Secondly, a change in wood density always reflects a change in the nature of the wood which may directly affect pulp quality. Wood density variations from 10 to 25 % have been reported to occur normally in the chip flow into primary refiners in northern spruce species (Cort et al. 1992, Fournier et al. 1992). If the average basic density of Norway spruce pulpwood chips arriving a TMP mill is 400 kg/m^3, for instance, this would mean up to ±100 kg/m^3 variation in the chip flow. Naturally, the variation in the wood density of single chips can be considerably greater.

According to Cort et al. (1992), the problem in controlling the refiner motor load, which is usually made with either the plate gap or hydraulic pressure, is that these control strategies do not compensate for the changing wood density and the result is a fluctuation in the refiner applied specific energy. These specific energy changes result in nonuniform refining and lower average pulp quality. Although the above fact is commonly known, it has not been investigated very much or at all (Fournier et al. 1992, Cort et al. 1992, Hill et al. 1993). Recent improvements in the production control of the refiner-based pulping systems, has diminished some of the above discussed disturbancies (Hill et al. 1993).

However, it should be borne in mind that to get a product of optimum quality, an uniform, highest quality wood is fundamental in any manufacturing process. With respect to this, there are reports on several TMP mills that have started a control strategy, according to which the received wood chips are classified, depending on their origin, as "high density" and "low density" wood, and pulped separately (Mercier 1987, Cort et al. 1992, Fournier et al. 1992, Williams 1993). These types of woodland and woodyard operations are being increasingly popular, being generally aimed, not to produce certain pulp properties from wood with a certain density, but to get pulp of high uniformity, which, in turn, contributes naturally to better overall TMP quality and power consumption efficency (see Braaten et al. 1993).

2.2.3 Summation

It can be stated that Finnish sprucewood (*Picea abies*), as it has relatively low average basic density, 380 kg/m^3, compared to most commercial softwood species, is one of the most suitable raw materials used in thermomechanical pulping in terms of obtainable pulp quality or power consumption level. Despite the fact, that the average basic density varies typically only 25 kg/m^3 within a single stem, great variation in basic density can occur between the stems, and pulpwood bolts arriving the mill. Namely, average basic density values ranging from aproximately 300 to 500 kg/m^3 has been reported in stems originating even from geographically restricted area. The most important factors determining average basic density in a spruce stem are the tree age and growth rate, the former having positive and the latter negative correlation with basic density. However, the variation of average basic density is moderate and considerably smaller than that of Scots pine pulpwood, irrespective to the size of stem or which part of the stem the bolts or chips originate from.

Since wood basic density is a gross wood characteristics, and give no direct information on the properties of pulpwood fibers, no correlation with either mechanical pulp quality or specific energy consumption has generally been found, except that between wood species. Within a species, only pulp tear strength and long fiber content would increase with increasing basic density. Since the wood basic density, unlike some other wood properties discussed in later chapters of this investigation, is not a good variable in predicting the TMP properties, rather uniform and constant wood density distribution in chips would be appreciated, when the objective is to manufacture pulp of high quality, but with low power consumption. The impact of great density variation which normally occurs in the chip flow and cannot be responded by a mechanical pulping system, is merely negative for TMP. In practise, this effect could be best offset, but not eliminated, by segregating roundwood assortments from origins typically having different average wood basic densities, such as young and old stands, or from rich and poor sites, and refining them separately.

2.3 Moisture Content

Wood freshly cut from a tree as pulpwood bolts or chips normally contains a substantial amount of water, a fundamental constituent of a living tree. Moisture in wood exists in two basic forms: *bound water* (or hygroscopic) within the cell wall and *free water* (or capillary) in liquid form in the voids of the wood. Much of this water, especially in the most recently formed sapwood, is located in cell lumens, but due to the hydrophilic nature of wood cellulose and hemicelluloses, the cell walls are also normally saturated with water. Exposed to most environments, freshly cut logs, pulpwood bolts, or fresh chips will start to dry, the rate of evaporation depending on the initial moisture content of the "green" wood, ambient temperature, and movement of the surrounding air (Skaar 1972). Wood matrix as a whole is strongly hygroscopic, and when dry, it absorbs water avidly (see e.g. Skaar 1972, Siau 1984, Fengel and Wegener 1989).

It is traditionally known that a sufficent moisture content, i.e., preferably fresh wood, is a key factor determining pulp quality in mechanical pulping, and as mentioned earlier, in Section 2.1.4, the temperature and extent of softening of wood matrix prior to defiberizing in thermomechanical pulping depends on the amount of water in cell walls. The content of moisture in wood has considerable impacts on the behavior and properties of wood itself, and, as will be shown later, its conversion to mechanical pulp. In this respect, perhaps the most important concept to affect the wood-water relationhips is the *fiber saturation point* (FSP). If there is just enough water to completely saturate the cell wall substance and no liquid water is present in the cell lumens, the wood is said to be at its fiber saturation point (Skaar 1972, Ahlgren et al. 1972), which moisture content corresponds with abrupt changes in physical properties of wood such as schrinking/swelling and mechanical strength of wood (Stamm 1967). The moisture content at FSP depends on e.g. wood species, temperature and basic density, and values from 27 to 33 % (o.d. basis) has been obtained for Norway spruce (Tamminen 1964, Koponen 1990, 1991).

Another factor of special interest for many pulping operations is the *pit aspiration* of conifer tracheids, since it reduces dramatically the permeability of wood. Namely, the water flow from a tracheid to another (above the FSP) occurs through small openings in the cell wall called pits (Siau 1984). The aspiration of pits, leading to closure of bordered pits, can occur in two mechanisms; when wood is subjected to drying and when heartwood is formed (see Section 2.8). This phenomenon is known to be very pronounced in Norway spruce and other spruces, the heartwood of which can become almost impermeable to liquids (Beauford 1991, Bierman 1993).

2.3.1 Variation in Moisture Content

According to a study by Hakkila (1970), the average green moisture content of Norway spruce pulpwood was 117 % ($\text{MC}_{\text{(dry-basis)}}$), and that for spruce sawlogs, was only somewhat smaller, being 112 % ($\text{MC}_{\text{(dry-basis)}}$). If presented on wet basis ($\text{MC}_{\text{(wet basis)}}$), the above values would be lower, about 50 % and slightly less (see Parham 1983a). Similar findings have been made by many investigators for Scandinavian grown spruce (see e.g. Nylinder 1959, Tamminen 1964, Okstad 1988) Studies of the moisture of green wood show that considerable variation exists among kinds of trees, between heartwood and sapwood in the same tree, and even between logs cut from different heights of the tree. There are also seasonal variation, geographical variation, variation according to site quality and variation between trees from the same site (see e.g. Skaar 1972, Siau 1984, Haygreen and Bowyer 1989).

The biggest source of variation of the green moisture content in a tree stem is the presence of heartwood and sapwood (see Chapter 2.8). Generally, the heartwood, i.e. cell lumens, of most softwood species does not contain noteworthy amounts of free water. In a living tree, the heartwood moisture content only rarely decreases below the FSP, which could result in abrupt physical changes in wood matrix. The following table (Table 2) indicates the green moisture contents between the heartwood and sapwood of nine North American conifers, and for comparison, Finland-grown Norway spruce and Scots pine.

It can be seen from Table 2 that there is considerable variation among wood species with respect to their green moisture contents. For the two Finnish softwoods, approximate values given on wet-basis ($\text{MC}_{\text{(wet basis)}}$), would be slightly under 30 % for heartwood and about 60 % for sapwood (see Parham 1983a).

Table 2. Average green moisture contents of nine softwoods grown in USA (Skaar 1972), and two Finnish softwoods (Jalava 1952). Values are based on ovendry weight.

Species	Moisture content, % Heartwood	Moisture content, % Sapwood
Cedar; Alaska	32	166
Cedar, western red	58	249
Hemlock, western	85	170
Douglas-fir, Rocky Mountain	30	112
Fir, noble	34	115
Pine, lodgepole	41	120
Pine, loblolly	33	110
Spruce, eastern	34	128
Spruce, Sitka	41	142
Scots pine	31	133
Norway spruce	33	146

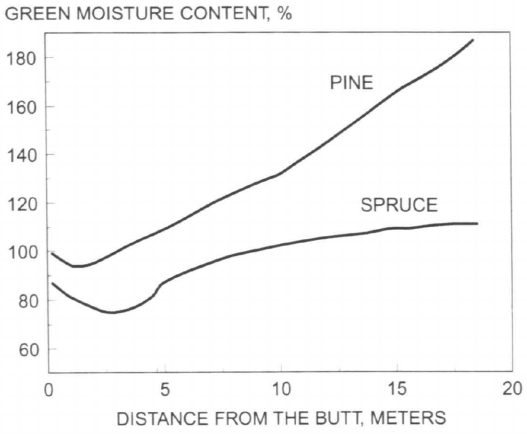


Figure 10. Variation in the average green moisture content (dry basis) along the stem height in Norway spruce and Scots pine, according to Tamminen (1964a, b).

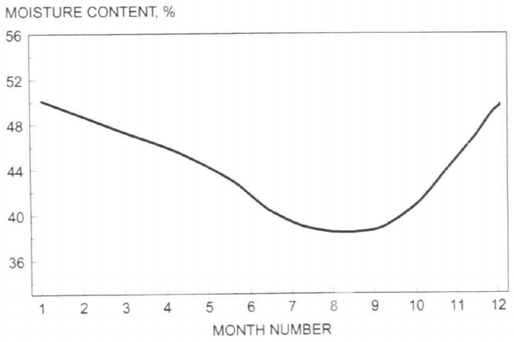


Figure 11. The relationship between green moisture content (calculated on wet basis) and time of delivery in Norway spruce pulpwood. On an average 34 stems were sampled each month (drawn from data by Okstad 1988).

In addition to radial variation of the green moisture content within a tree, there is also a pattern for vertical variation. In many softwoods, the average green moisture content decreases first from butt to about 10 % height level, and then increases rapidly to the top, as illustrated for spruce in Figure 10. Since the average green moisture content of heartwood is found to be more or less the same in all height levels, and that of sapwood to increase towards the top, most of the variation in average green moisture content can be explained by the proportion of heartwood in a stem (Section 2.8). In the outer sapwood of Scots pine, the green moisture content has been reported to increase from 120 % to 180 % (Nylinder 1950). In Norway spruce, the increase is not that dramatic (from 155 % to 180 %), according to the same study. This is mainly a result of a corresponding decrease of the wood specific gravity from butt to top (Tamminen 1964, Uusvaara and Pekkala 1979).

With respect to longitudinal and radial moisture differences discussed earlier, there is noticeable variation in the amount of water present in stem in Nordic countries, depending on time of the year, i.e. climate conditions (Jalava 1952, Hakkila 1962, Okstad 1988). Generally, the logs are driest in the summer and the water content is highest in around December, in the dormant season of trees, as shown in the following figure (Fig. 11). Similar results has been obtained elsewhere for Finnish spruce and pine by Hakkila (1962). The above seasonal variation is naturally of interest, since the moisture content of wood delivered to a mechanical pulping is relatively low in the late summer and early fall harvesting season.

It should be noted that within any species there is also considerable variation depending upon the site, age, and volume of the tree (Jalava 1952). When the age and volume of a tree is being considered, it is mainly the percentage of heartwood and wood specific gravity and, an their variation, that largely affect the green moisture content. If these two factors are eliminated, considerable variation occur between equal-aged stems from the same site. It is widely believed that genetical reasons account most of this variation (Panshin and de Zeeuw 1980, Zobel and Buijtenen, van 1989.)

2.3.2 *Influence of Wood Moisture on TMP Manufacture*

Since most mechanical pulping systems operate and favour only freshly delivered wood, the dry matter content of final chip furnish is largely determined by that of green wood. Stored wood and chips may have about 15–25 % moisture content, and should not be used for mechanical pulping (Nyblom 1979). It is commonly known that in chemical pulping, the impact of initial wood moisture is not as noticeable as in mechanical pulping. In wood grinding (SGW), the moisture content of wood is critical determining the pulp quality. In mill conditions, wood bolts of which moisture content is below 40 % (dry-basis), is not preferred for grinding process (see e.g. Parham 1983, Leask 1987b). Most pulp properties remain constant, as long as the moisture content remains above this. Wood that has been dried to a lower moisture content will produce a lower strength pulp with generally poorer properties. However, in his experiments de Montmorency (1964) found that rewetting dry wood from 27 to 52 % gave approximately similar pulp properties than the original moist wood. Remoistening once-dried bolts is not usually feasible in commercial scale.

In the manufacture of thermomechanical pulp (TMP), the effect of moisture content is believed to be similar, but not that dramatical than in wood grinding (deMontmorency 1962, Hartler 1977, Eriksen et al. 1981, Leask 1981). Generally, as wood moisture content decreases to a low level, the quality of TMP is affected as follows (Brill 1985); shives-content increases, long fiber content decreases, fines content increases, tear and tensile strength decrease, bulk increases and linting problems in printing increase. Moreover, if the pulp freeness level is intended to be kept constant, the pulp energy consumption can increase.

In the preheating of TMP chips, the main modification of the wood is a partially irreversible softening during which bonds are broken in the wood structure (Hartler 1977). The softening is strongly influenced by water; the higher the water content the lower the softening temperature or the more extensive the softening at a given temperature (see Section 2.1.4). The moisture which is relevant in this connection is obviously the water positioned in the fiber wall in intimate contact with the wood components. Furthermore, Eriksen et al. (1981) has observed, that retention time of chips in preheater is highly dependent on the amount of water in chips, the main part this water to be heated in preheater being located in the lumen. Both theoretical calculations and his practical experiments show this dependence on the specific heat capacity. According to this moist chips (ca. 60 %) require twice retention time in the presteamer than dry chips (ca. 10 %) to reach a desired temperature under the same presteaming conditions. Unfortunately, adjusting the retention time to the moisture content of chips, is not sufficently practiced in mills.

Hartler (1977) has studied the effect of the initial moisture content of chips on the quality of TMP in his pilot trials. According to him, the wood moisture content in TMP manufacture is not as critical as it is in grinding. The moisture content of wood should definitely be above the fiber saturation point, a fact supported also by Eriksen et al. (1981). As mentioned before, the water content at complete wood saturation point in softwoods is directly related to wood density, the lower the wood density the higher the saturation moisture content. Hartler's experiments have confirmed two prerequisites for TMP;

1. The *fiber saturation point* (FSP) should be reached prior to the softening in the preheater and
2. Moisture, corresponding to fully water saturated wood should be added prior to the entrance of the refiner

Both these should be fulfilled to reach the maximum TMP strength properties. Unless the chips are fully water saturated initially, a rapid penetration of the required extra water must be facilitated. The best way is to heat with steam and thus fill the voids with water vapor and then add somewhat cooler water. Hartler's (1985) experiment show that up to 10 % saving in energy can be achieved in TMP if the chips are compressed strongly in a feeding screw followed by expansion in water. He concluded that the compressed wood mass attains an extra high moisture content upon expansion in water, compared to subsequent expansion in steam.

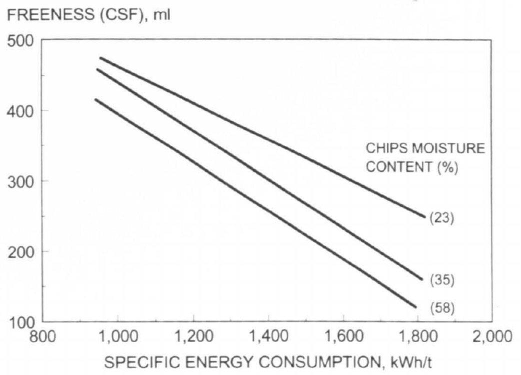


Figure 12. The effect of chip moisture content ($MC_{\text{wet basis}}$) to the specific energy consumption in refiner pulps from black spruce (Miles 1990). The percent moisture content is shown in parentheses.

Table 3. TMP pulps from softwood chips of different moisture contents. Pulp properties are given at 100 ml (CSF) freeness level (Barbe et al. 1993).

	Dry chips	Normal Impregn.	Water Impregn.
Solids content, %	54.4	45.3	35.7
Specific energy, kWh/mt	1750	1885	2060
Bauer McNett			
R16 (%)	11.8	25.0	32.7
R30 (%)	25.0	20.5	17.7
R100 (%)	32.7	26.4	20.0
R200 (%)	5.9	5.0	5.0
P200 (%)	21.4	25.0	23.6
Shives content, %	1.17	1.22	0.78
Tensile index, Nm/g	42.5	49.0	51.3
Burst index, kPa m^2/g	2.11	2.80	3.00
Tear index, mNm^2/g	7.8	9.0	10.3
Wet strength, N/m	60	75	91
Light scattering coeff., m^2/kg	44.6	42.5	43

It is widely believed, that if TMP production is kept at constant freeness level, the required power input increases with decreasing moisture content of chips. According to Nyblom (1979), when the dry matter content of softwood chips increased from 50 to 70 %, there was 20 % increase in the specific energy consumption. The following chart (Fig. 12) shows the relationship between the specific energy consumption and freeness level at different chip moisture contents. Miles (1990) refined atmospherically black spruce (*Picea mariana*) chips and found that at a given specific energy consumption, the freeness increases with the solids content of the chips. This is also confirmed by de Montmorency (1962), who found that dry chips produce weak and "pulver-like" mechanical pulp with a high share of broken fibers.

Somewhat contrary to the above, however, Eriksen et al. (1981) concludes that the moisture content of the chips could be varied within wide limits without any significant influence on the energy consumption and the pulp properties. Only when the moisture content is brought below the FSP, both properties are negatively influenced. He pulped thermomechanically Norway spruce in pilot scale. Some TMP properties at different chip moisture levels, reported by Barbe et al. (1993) are shown in the following table (Table 3). The wood species used was black spruce (*Picea mariana*), which have quite similar pulping properties compared with Norway spruce.

Pulp strength properties are obviously affected, if dry chips are used in TMP manufacture, as can be seen clearly from the above table (Table 3). Namely, all important strength properties are poorer with the driest chips, at the same freeness level. This is supported by Tyrväinen's (1993) pilot-scale TMP refining experiments with *Picea abies* heartwood and sapwood. Moreover, all TMP fiber and particle properties were more or less affected by the moisture content of wood, including shives content, average fiber length, long fiber content (Bauer McNett R16 and R30 mesh). A decrease in tear strength is mainly due to shorter average fiber length. The tensile index is negatively influenced, because of shortened average fiber length, and possibly because of poorer fiber development during refining of dry chips (Eriksen et al. 1981, Hartler 1977, 1985). Contrary to the above, according to Hartler (1977), the initial wood or chip moisture content have no significant effect on the above fiber and particle properties, except shives content. The following figure shows the relationships between tensile index and energy of spruce TMP, at different moisture levels (Fig.13).

It is known that in groundwood (SGW), pulp brightness is not found to depend significantly on the wood moisture content (deMontmorency 1964). Similar results has been obtained for TMP, where no direct effect of wood moisture content on brightness has been found (Brill 1985, Höglund and Wilhelmsson 1993). In some cases, though, Nyblom (1983) found a significant loss in pulp brightness, a drop of 10 ISO units, as the driest wood were used in TMP manufacture. The best pulp brightness can definitely be obtained, when fresh wood is used in the process. Storage of wood, in any form and length, affects pulp brightness not only via lowered moisture content, but other effects such as sap staining by micro-organisms, chemical reactions of extractives etc. (Nyblom 1979, Pennanen et al. 1993).

As the pulp brightness is a function of light adsorption and light scattering properties, wood moisture may have an indirect effect on it. If dry wood is expected to produce TMP that have a higher share of fines and medium fiber fractions, which would contribute higher light scattering coefficent and thus elevated brightness, too. But in this case, the properties of fractions would be of greatest importance to determine pulp brightness. In his experiments, Eriksen et al. (1981) found that chips with a moisture content below the fiber saturation point gave higher light scattering than chips with a moisture content above.

Since much contradicting data exists of the interrelationships between wood moisture and pulp quality, and wood does not necessarily behave in a similar manner in grinding than in refining, it seems that the question is whether water enough can or cannot be applied to the chips before defibration. Rewetting of wood is said, in most cases, to result in wood with more or less the same quality as fresh wood, when subjected to refining. However, any brightness lost during the storage period (e.g. due to staining, chemical reactions etc.) cannot be regained (deMontmorency 1962 and 1964, Leask 1987a). It is difficult to remoisten pulpwood logs with aspirated pits, that is often the case with spruce heartwood and once-dried logs from storage. In TMP manufacture, where wood is used as chips, the feasibility of remoistening wood before being fed to the refiner is thus much greater, than in wood grinding.

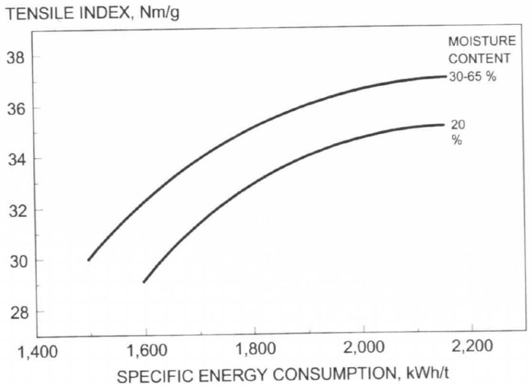


Figure 13. Relationships between tensile index and energy consumption in pilot scale Norway spruce TMP for various moisture contents (Hartler 1985).

An important function of the hot water chip washing system, in addition to removing unwanted material, is to add moisture to the chips helping to uniformize the moisture levels and, off course, to preheat the chips to soften the wood matrix. This is necessary especially in atmospheric refining processes, where chip presteaming is not used. The washed, pumped chips are then dewatered before distribution to the impregnator or the refiner lines in order to avoid uncontrolled water, according to Beaudry (1987). Furthermore, Hartler (1977) has noted, that there is consequently some increase in moisture content (from 44.4 to 50.6 %) as a result of passage through the chip washer, but the added water is largely present only on the chip surface. When the TMP chips are presteamed atmospherically, the air present in the fiber lumen is replaced with water vapour. During this presteaming stage, the average moisture content of chips increases. Jackson (1985) found the average moisture content of spruce chips to increase by 3 %, from 52 % to 55 %, when atmospherically presteamed for 2 minutes. If presteaming was followed by water impregnation, the average moisture content increased up to a level of 64 % and slightly more depending on impregnation time.

In the light of the foregoing, it is possible to apply more water in TMP process into dry chips, if there is enough time between chip washing and preheating, and appropriate moistening conditions are used. Instead of that, pulp mills would naturally prefer fresh wood of even quality (Nyblom 1979). Another methods to apply high and even moisture content to the TMP chips are high compression chip presses, that are found to be efficient in chemimechanical pulping (Hartler 1985, Barbe et al. 1993).

At any moisture content level supplied, it is important to minimize the moisture variability, i.e. the evenness of moisture content and its distribution in chips, in TMP manufacture. This is due to a fact that the most important variable in chip refiner, is the *refining consistency*. According to Miles at al. (1990), it determines the quality of pulp that can be obtained for a given specific energy. Consistency in the refining zone and that of resulting pulp is largely determined by the amount of wood and water, coming in with the chips plus the water fed to the refiner. Practically all chip refiners are volumetrically fed, thus being subject also to production rate variation, with varying consistency. This causes process unstability, and therefore unacceptable pulp (Hill et al. 1993). Barbe et al. (1993) has shown that the use of water impregnation of wood chips evens out size and moisture content of the chips for production of a more uniform TMP in addition to improving strength pulp quality.

2.3.3 Summation

Since water has a key role in all living organisms, "green" wood in living trees contains a high proportion of water which varies within and between Norway spruce stems, not to mention the variation within a cutting season. In wood, procured to the pulp mill, the average content of moisture is usually above 40 % (wet basis), which facilitates all mechanical pulping operations. However, since the greatest source of variation in moisture content is that between the dry heartwood (33 %) and wet sapwood (60 %) within a same stem, exceptionally dry wood can arrive to the mill. This would be the case of large, old spruce stems with a high content of heartwood.

The major contribution of wood moisture in TMP process is the mechanism called "softening" of the wood matrix, necessary for defiberizing and fiber development in refining. As a conclusion of wood moisture content in TMP manufacture, the following can be stated. TMP process is not as dependent on the initial wood moisture content as is the SGW process, due to better feasibility to remoisten dry chips. However, the optimum TMP quality will always be achieved with the usage of freshly cut wood. The moisture content of chips can vary within wide limits, without any significant influence on the energy consumption and the pulp properties. When the moisture content is below the fiber saturation point the pulp properties are however negatively influenced. When extremely dry chips, say 10–30 % moisture content that can occasionally be the case, are used and not enough water cannot be applied to the fibers prior to softening in the preheater and prior to the entrance of the refiner, optimum TMP quality cannot be reached. Firstly, there is an increase in the specific energy consumption and shives content. Secondly, the pulp strength and fiber properties are influenced negatively. Pulp optical properties are not, or at least not negatively, much related to wood moisture content. Perhaps the most harmful effect caused by continuous moisture variation in chips, is the direct bearing it posses on the refining consistency. This is known to produce pulp of uneven quality, and cannot be sufficiently contolled in present-day refining systems.

2.4 Fiber Length

In Norway spruce, approximately 95 % of the woody cell matrix is composed of longitudinal prosenchyma cells (Huber and Prütz 1938), i.e. *tracheids*, which can be also termed interchageably *fibers*, as called in the pulp and paper making industries. The origin of xylem fiber morphology, including the *fiber length*, is the activity of the cambial zone. Unlike the fiber cross-sectional dimensions, fiber length is strongly under genetical control (Larson 1962, Buijteten, van 1967), however, it can also be altered to a certain extent by changing growing patterns silviculturally. A correlation between shorter fiber length and rapid stem diameter was reported very early by Lee and Smith (1916), and the important physiological link between rate of stem diameter growth, the number of anticlinical cell divisions taking place in cambium, and the average fiber length which results, has also been established (Bannan and Baily 1956, Larson 1969). It is now more than 120 years since Sanio (1872) made his pioneering investigations on the within-tree variation of tracheid length in Scots pine, the results of which were summarized later for all conifers by Bailey and Shephard (1915). Variation in the fiber length of Norway spruce, being of highest importance for a pulp mill, is shortly discussed in the following section.

2.4.1 *Variation in Wood Fiber Length*

Comprehensive data on tracheid length and its variation has existed since the earliest investigations made of Norway spruce wood properties (see e.g. Bertog 1895, Hartig 1898, Mork 1928b, Klem 1934). The average tracheid length in Finland-grown Norway spruce stemwood varies approximately from 2 to 4 mm, and is mainly influenced by tree age (see e.g. Bruun and Slungaard 1957, Saarnijoki 1966). In their extensive material collected in Sweden, Nylinder and Hägglund (1954) found the average fiber length in spruce being 3.11 mm (standard deviation 0.30 mm). Atmer and Thörnqvist (1982) found a mean value of 2.88 mm (standard deviation 0.56 mm) for the average tracheid length in a Norway spruce stem, of which age was 96 years. Minimum value was 0.95 mm and maximum value 3.88 mm, respectively. All these values can be considered as typical average fiber lengths in Scandinavia-grown spruce (native) stemwood.

As the most wood properties, cell length varies greatly both within and among trees, not to mention variation between different wood species, a fact that often affect the technical value of the species in question. In a Norway spruce stem, the fiber length varies depending on its vertical and radial position in stem, and its rate of growth, this variation following closely the early foundings of "Sanio's laws" mentioned earlier. Within a stem, the tracheid length is most strongly affected by wood age, i.e. radial position (ring age). Of course, in a forest stand, there is similar type of variation between the stems for same reasons, but this variation is much smaller compared to within-tree variation (Dinwoodie 1961).

Table 4. The average tracheid length and its variation at DBH in radial direction in Norway spruce stems (Saarnijoki 1966).

Radial location in the stem	Average fiber length and its variation, mm
Inner heartwood	1.9 (1.28–2.70)
Middle zone	3.0 (1.69–3.88)
Outer sapwood	3.7 (2.80–4.29)

As a general cross-sectional pattern, the tracheid length is shortest next to the pith. The increase outward with age is at first very rapid in the juvenile period (see Section 2.7), then slows down considerably between ages 10 to 30 (in Norway spruce) and thereafter, as mature wood begins to form, increases very gradually with seasonal fluctuations and may or may not completely level off (Thörnqvist 1990, Kucera 1994). In softwoods, the increase of length of tracheids from pith towards the cambium occurs in all stem height levels. Thus, the longest cells are formed by old cambium (Megraw 1985). The great differences in the average tracheid length between the inner heartwood and outer sapwood are clearly indicated in Table 4. For this study, Saarnijoki (1966) examined 30 Norway spruce stems, aged from 70 to 100 years, from two forest stands in Southern Finland. Measurements were taken at breast height (DBH). The pattern for fiber length in radial direction can be observed also in Fig. 14.

As in most conifers, the variability of Norway spruce tracheid length with height, i.e. in vertical direction of a stem, is more regular than that with distance from the pith. Within a given growth ring, tracheid length first increase with increasing height above the ground and then, having reached a maximum, decreases towards the tree top. Usually, for a large number of conifers, maximum tracheid length occurs at a level of 30–40 % of the total height (Dinwoodie 1961). The pattern for vertical variation of fiber length in spruce, is shown in Figure 15. Within the inner annual rings, the length of tracheids may start to decrease upwards directly from the stump level (Mork 1928). The increment towards the cambium is noticeably faster in the upper parts of the stem (see Fig. 15).

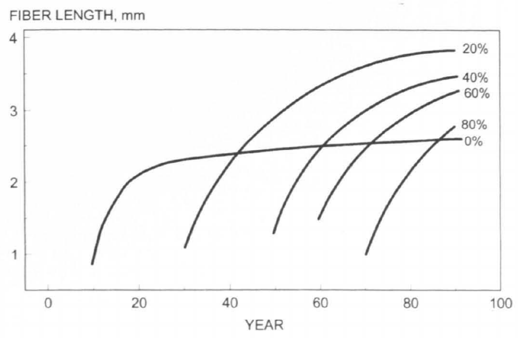


Figure 14. Mean fiber length in a section through a spruce (*Picea abies*) at different percentages of the stem's height. Redrawn from Atmer and Thörnqvist (1982).

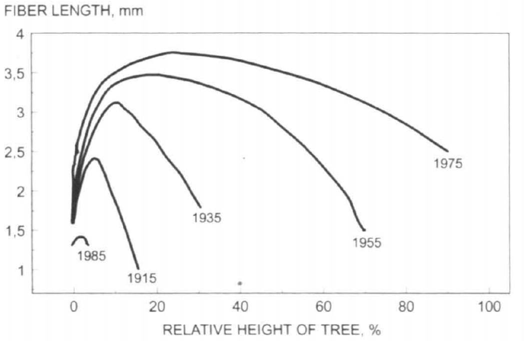


Figure 15. Variation of tracheid length in selected growth rings of a 96-year-old Norway spruce as a function of relative height in the stem (Atmer and Thörnqvist 1982).

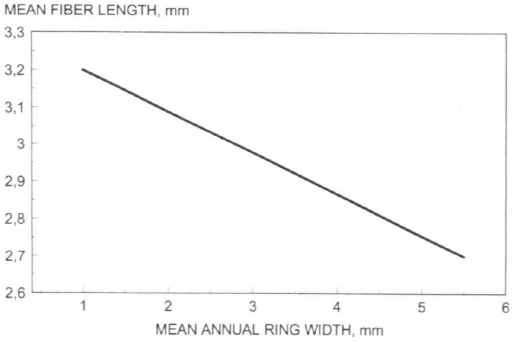


Figure 16. The influence of mean annual ring width on the length of fibers in Norway spruce mature stemwood (Nylinder and Hägglund 1954).

The variation of tracheid length in conifers, in both radial and vertical directions,is strongly influenced by the occurrence of juvenile wood, the fiber length being considerably smaller in this tissue type compared to mature stemwood (see Section 2.7). Therefore, the changes in tracheid length that occur within the zone of juvenile wood should always be considered separately from the subsequent and less drastic changes that take place within the mature wood (Larson 1969, Thörnqvist 1990).

As discussed before (Section 2.4), when coniferous tracheids are formed in cambium, the rate of growth (ring width) is a factor, which can largely determine the final fiber length. In a same tree, the average fiber length in a narrow growth ring is thus greater than in a wide ring. This is also true between slow- and fast-grown, but equal-aged trees, in the same forest stand (Zobel and Buijtenen, van 1989). Moreover, trees growing in sites of moderate fertility have had somewhat longer fibers than the ones growing on the best sites, as determined for Norway spruce for instance by Helander (1933), Nylinder and Hägglund (1954) and Hillebrandt (1960). Unlike as could have been expected from the rate of growth, the average fiber length seems to be about 10 % shorter in northern parts of Scandinavia than in the south (Nylinder and Hägglund 1956, Brill 1985). The relationship between growth rate and fiber length in Norway spruce is shown in Fig. 16. However, some investigators have found the above correlation to be less clear, or limited to a smaller range of ring widths (Dinwoodie 1961, Petrik 1968).

2.4.2 *Influence of Fiber Length on TMP Manufacture*

The impact of fiber length on paper properties is well recognised, though not highly quantified. It is intuitively obvious that longer fibers have a greater number of interfiber bonding opportunities per fiber than shorter fibers. The relationship between fiber properties and paper properties has been the subject of several excellent reviews (see e.g. Dadswell and Wardrop 1959, Dadswell 1963, Dinwoodie 1965, Buijtenen, van 1967 and 1969, Kibblewhite 1981). Often the importance of cell length has been overemphasised in the literature. A common belief is that short cells are responsible for deficiencies in certain paper properties when, in fact, the main problem relates to deficient cell wall thickness. Thus, a greater importance was formerly attributed to fiber length than present. It influences many paper properties but seems to be decisive only in the case of tear strength (Megraw 1985). Even here, however, the ratio of fiber length to diameter or wall thickness might be a more important factor (Dinwoodie 1966, Paavilainen 1993).

The fiber length is an imperative factor determining pulp properties, when softwood fibers are compared to hardwood fibers, or, in the case of juvenile wood, where the length of tracheids is usually only a half of that in mature stemwood (Zobel and Buijtenen, van 1989). However, pulps made from woods having relatively long fibers, like from Sitka spruce (*Picea sitchensis*), for instance, typically having well over 5 mm average wood fiber length, do not necessarily give stronger pulps, than made from northern spruces that have only about 3 mm average fiber length (Clark 1985). Obviously, there seems to be a threshold value of cell length where increasingly longer cells have little effect on the quality of the product. According to Dadswell and Wardrop (1959), this threshold value in pulp is about 2 mm for making kraft paper with an acceptable tear strength. During manufacturing, longer cells break more than the shorter ones. It is when cells are near the "threshold length", depending much on the pulp and paper product in question, that cell length variation can be of primary importance with regards to acceptable product quality.

A comprehensive study of the influence of fiber morphological properties, among them fiber length, on the Norway spruce and Scots pine kraft pulp fiber and paper properties is made by Paavilainen (1993). However, chemical pulps are consisted mainly of long and slender fibers, whereas mechanical pulps are consisted of rigid long fibers, majority of the pulp's substance being shortened and broken fibers, their fragments and fines material of different origin. Therefore, it is more than obvious that there are differences between the two types of pulps, when the effect of fiber length is being considered. Several attempts to characterise mechanical pulps, and especially their strength properties have been made (see e.g. Forgacs 1963, Mannström 1968, Shallhorn and Karnis 1979). The pulp fiber length factor has always been included to these assumptions, but obviously far too often these theories fall to the misconception that there is only one type of mechanical pulp, or earlier fundamental studies have been concentrated mainly on groundwood (SGW) and refiner mechanical pulps (RMP), but not TMP (see. e.g. Mohlin 1979, Jackson and Williams 1979, Corson 1979, Kurdin 1979, Honkasalo and Ebeling 1981, Laamanen 1983, etc.).

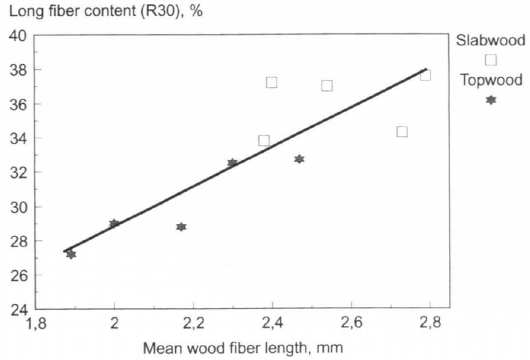


Figure 17. Long fiber content (R30) of TMP at CSF 140 ml, vs. mean wood fiber length. Pulps are made from Norway spruce slabwood and topwood (Brill 1985).

In the manufacture of mechanical pulps, there are two important pulp properties related with the original fiber length in wood. These pulp quality factors are: *pulp long fiber content*, and the *pulp average fiber length* (and its distribution). In addition to, being easily checked in the routine pulp quality control, both properties give indication for the paper maker of the paper making potential of a mechanical pulp in question. As could have been expected, a good correlation between the mean fiber length of wood and the TMP long fiber content as well as the average fiber length, have been found (see e.g. Brill 1985, Hatton and Cook 1990, Corson 1991). The following figure (Fig. 17) shows the relationship between the mean wood fiber length and TMP long fiber content (retained on Bauer McNett 30 mesh screen).

In TMP manufacture, due to the softening caused by elevated process temperature and the presence of moisture in cell walls (Section 2.1.4), the fiber separation in wood matrix is expected to occur mainly along S_1- and S_2-layers, producing more intact fibers than, for instance, in conventional wood grinding (Kurdin 1979). Excellent strength properties of TMP, compared to other mechanical pulps, are often explained with high long fiber content and average fiber length. According to Lindholm (1981a), typical average fiber lengths for TMP, PGW and SGW pulps (at CSF 120 ml), made from Norway spruce, were 1.85 mm, 1.68 mm and 1.33 mm, respectively. Also the long fiber content is significantly higher in TMP compared with other mechanical pulps, at the same freeness level (see e.g. Honkasalo and Ebeling 1981, Lindholm 1984, Paulapuro and Laamanen 1988, Haikkala et al. 1990).

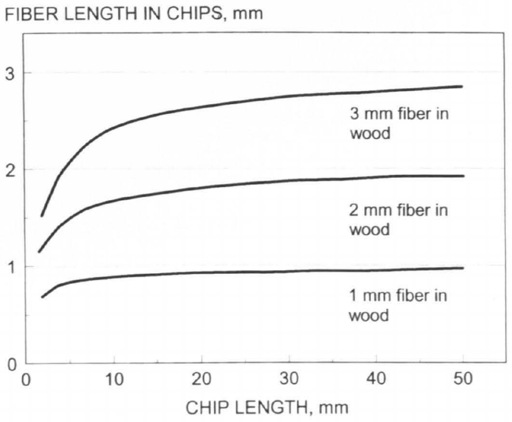


Figure 18. The theoretical average fiber length in comminuted wood as a function of the particle length (chip length in fiber direction), when native fiber length in roundwood is 1, 2 or 3 mm. (Hakkila 1989).

The native fiber length of roundwood do not automatically result in the same *fiber length distribution* in pulpwood chips, but is always somewhat lower in chips. The geometry of the pulpwood chip particles is determined by the cutting techniques (Parham 1983, Hakkila 1989). A chip particle contains a number of damaged fibers. This number will in theory increase with decreasing particle size as shown in Figure 18. Therefore, a decrease in pulp long fiber content is expected at increasing chip fines content or when the average particle length is decreased (Brill 1985). However, to obtain uniform pulp, each pulping process has its optimum or preferred chip geometry, including the *chip length* distribution.

The average fiber length in the obtained TMP is always much shorter than that in the wood raw material, which the pulp is made from. Of course, type of wood (species, summerwood content, etc.) used in refining, roughly determines to which extent the pulp fiber length can be retained in optimal process conditions (Höglund and Wilhelmsson 1993, Corson and Ekstam 1994). Moreover, there is a quite good agreement, that the pulp average fiber length is largely determined in early stages of refining, in the fiber separation stage (May 1973, Leask 1981, Corson 1989, Stationwala et al. 1991, Karnis 1993) The average fiber length, expressed usually as a length-weighed average fiber length, decreases quite linearly as a function of the freeness level, i.e. the degree of refining. The preferred freeness level is usually set as a combination of preferred pulp properties for a certain end-use. Thereafter, how well the original fiber length of wood is best retained during refining depends, though, largely on process conditions. Thus, harsher the process conditions and lower the desired freeness level, extensive fiber cutting can occur (see e.g. May 1973, Pearson 1983, Atack et al. 1983).

Generally, long pulp fiber length in TMP is expected to result in high tear strength but low printability and poorer formation. On the contrary, short fiber length equals good paper smoothness and opacity but low tear (Mannström 1977, Paulapuro et al. 1983, Leask 1987a). Therefore, from the pulp manufacturer's view point, the wood raw material giving the best strength potential for TMP, is the sawmill chips (Corson and Richardson 1986, Hatton and Cook 1990, Tyrväinen 1993). In Forgac's (1963) extensive studies, all mechanical pulp strength properties, both for dry and wet sheet, increased with increasing average pulp fiber length. According to more recent studies, where also thermomechanical pulps are studied, the effect of fiber length on the tensile strength of dry sheet, is not so clear (Jackson and Williams 1979, Mohlin 1979, Corson 1979 and 1980, Laamanen 1983, Paulapuro and Laamanen 1983, Brill 1985, etc.).

The positive correlation between the TMP average fiber length and the paper tear strength and wet web tensile strength is clear, though. The crit-

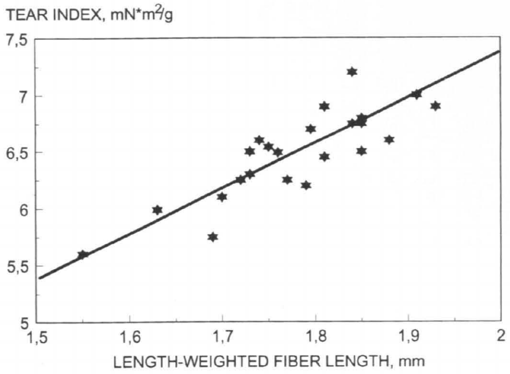


Figure 19. Tear strength vs. average fiber length for spruce TMP. (Kajaani Fiber Analyzer... 1986).

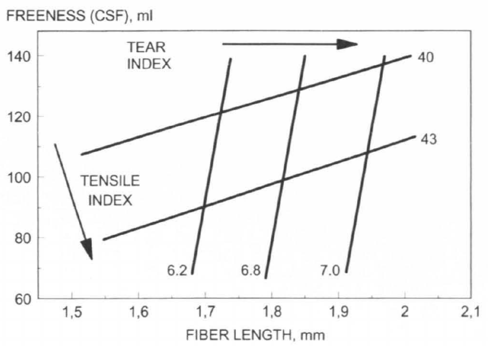


Figure 20. Quality chart for TMP newsprint pulps, comparing tear and tensile indexes. (Kajaani Fiber Analyzer... 1986)

ical properties of newsprint, for instance, are the strength properties, especially tear strength for runnability, and opacity (Nordman 1987). It is largely recognized that the most important factor determining TMP tear strength, at low bonding degrees, is the pulp fiber length (Corson 1980, Brill 1985, Hartler 1985). Furthermore, any reduction of TMP average fiber length cause a significant reduction in tear strength, which can be explained with the commonly used tear strength theory (see Shallhorn and Karnis 1979). The following figure (Fig. 19) shows the relationship between the tear strength and the average fiber length in TMP. It can be seen, that if TMP average fiber length decrease from 1.9 mm to 1.7 mm, the tear index value decrease over 10 % from the value 7.0 $mN \cdot m^2/g$.

According to Nordman (1987), a high mean fiber length is essential for the critical properties of wet web tensile index and tear index, the properties that largely determine the behavior of the pulp on the papermachine and its end-use operations. While use of high mean fiber length may cause a drop in some other parameters, such as pulp optical or printing properties, this loss must be remedied by giving the long fiber additional refining treatment (Kurdin 1979, Jackson 1979, Corson 1980). This, in turn, will give further increase in the wet web tensile index and will not affect adversely the tear index.

Brill (1985) has found a positive correlation between the pulp tensile strength and mean wood fiber length. He refined thermomechanically Norway spruce to the freeness level of CSF 140 ml. Slabwood with higher fiber length gave better tensile index, than wood from tree tops. Other investigators have not found that good relationships between those two properties, because tensile strength is a complex paper property that seems to be controlled mainly by the bonding properties of mechanical pulp particles, and only to a certain extent by pulp average fiber length (Jackson and Williams 1979, Mohlin 1979, Corson 1980, etc.). Therefore, the tensile strength is highly dependent on the pulp freeness level, the lower freeness, in principle, resulting in better tensile strength of TMP. However, it should be pointed out that at the same freeness level, the longer average fiber length in pulp, the better tensile length. This is illustrated in the following figure (Fig. 20).

According to Corson (1980), the long fiber and the fines fractions are presumed to be the most important fractions, and the medium and the short fractions of lesser value for TMP strength properties. This is supported also by Lindholm (1981a, 1981b, 1984) and Mohlin (1979). To the present knowledge, not only the proportion of the long fiber fraction, or the average fiber length, but especially the quality of different fractions, i.e. their bonding potential, is largely responsible for TMP strength properties (Mohlin 1979, Laamanen 1983, Lindholm 1981a, 1981b, 1984, Heikkurinen 1992). It must be also emphasised that the wood characteristics, among them fiber length, referred to in this theoretical part of the study are often interrelated. It is therefore difficult to decide how they influence for instance a specific strength property of pulp and paper. Moreover, different pulps and different wood species and type of wood respond differently, too. With respect to the above, it is therefore often difficult to quantify effects caused by a single wood property.

2.4.3 Summation

The average length of Norway spruce stemwood fiber, varying approximately from 2 to 4 mm, falls well within those found in most commercial softwoods. The length of softwood tracheids is primarily determined by the frequency of anticlinical divisions occurring in cambium, and is strongly genetically controlled. Generally, faster tree growth rate, as in managed forests or better sites, produces shorter fibers than slower growth, as on poorer sites or unmanaged forests. However, this environmentally controlled variation is minimal compared to that occurring within a single spruce stem, caused by age. Namely, average fiber length increases rapidly from about 1 mm, nearest the pith, to about 2–2.5 mm at 25th year-ring, whereafter it continues to increase more slowly towards cambium, reaching up to 4 mm average lengths in old mature spruce stem. The average fiber length is, thus, highest in sapwood closest to the bark, at the base of tree or about 30 % stem height level, wherefrom it decrease towards the tree top. It is obvious, with respect to stem age and location in the stem, that the average fiber length distribution in wood arriving the pulp mill, can be effectively controlled.

To date, the effect of fiber length on pulp properties has generally been over-emphasized in literature, since it is often the fiber cross-sectional dimensions which determine pulping properties of a wood species or type of wood. However, both in chemical and mechanical pulps, the pulp average fiber length has a strong positive correlation with pulp tear strength. In mechanical pulps, this is despite the fact that original wood fiber length does not transmit directly to TMP (is considerably lower) or, only about 40 % of pulp particles consists of fibers, the rest being finer particles. A small reduction, say from 1.9 to 1.7 mm, average pulp fiber length can cause over 10 % reduction in TMP tear index. Most wet web strength properties at a paper machine are being enhanced by long average fiber length in mechanical pulp component. Tensile strength of a dry TMP sheet is mostly controlled by bonding properties of pulp fractions. However, at the same freeness level, the longer average pulp fiber length result in better tensile strength. The fiber length have slightly negative, or no impact on TMP sheet and optical properties.

2.5 Fiber Diameter and Cell Wall Thickness

The two fiber cross-sectional dimensions – *fiber diameter* (*or fiber width*) and *cell wall thickness* – are generally known to have a major impact on pulp and paper products. Factors that govern the formation of wood fibers, including cell growth in size, wall substance deposition, and lignification, are associated for the most part directly with the activity of the tree crown and availability of nutrients in the cambium. However, much of the within-tree variation that occurs in cell cross-sectional dimensions is of genetical origin (see e.g. Larson 1962 and 1969, Bannan 1967, Philipson and Butterfield 1967, Gardiner 1978, Megraw 1985, Kucera 1994). It is true that the fiber wall ultrastructure, i.e., various cell wall layers and fibril orientation in it, can have a decisive role in the behavior of fibers in pulp and paper making, however, it is not the main scope here. Fiber cross-sectional dimensions can be also interrelated to other wood properties, such as basic density, existence of earlywood/latewood, or juvenile wood, thus, some of these aspects are discussed in appropriate sections (Sections 2.2, 2.6 and 2.7). Because it would often be difficult or unjustified to separate the variation in fiber diameter and cell wall thickness in wood, as well as their effect in pulping operations, these two properties are being treated together in this chapter.

2.5.1 Variation in Tracheid Diameter and Cell Wall Thickness

Compared to variation in cell length, the within-tree variation in tracheid diameter, and especially wall thickness has been investigated to much less extent. Among commercial coniferous pulpwood species, Norway spruce fibers are relatively small in diameter and have thin cell walls (Isenberg 1980, Malinen 1986). The average *tangential fiber width* in Scandinavian grown spruce (stemwood) varies from 21 to 40 µm (Trendelenburg 1939, Nylinder and Hägglund 1954, Ollinmaa 1959, Bruun and Slungaard 1957). Softwood tracheid width is more constant in the tangential direction than in the radial. In softwoods, the *radial fiber width* in earlywood normally exceeds tangential width but is normally much less than the tangential width in fully developed latewood. The cell wall thickness in earlywood tracheids vary generally from 2 to 4 µm, and in latewood from 4 to 8 µm. A calculated value for the average cell wall thickness in Finland-grown spruce is 3.69 µm, basing on Ollinmaa's (1959) extensive study.

However, like in the case of cell length, also the *tracheid diameter and cell wall thickness in softwoods show typical patterns of variation, firstly from pith to bark, and secondly, along the stem length.* The relative change in the cross-sectional dimensions is usually less than that for tracheid lengths. In conifers, most of the within-tree variation in tracheid cell wall thickness and radial diameter is explained by the concept of earlywood and latewood. When plotted, the variations in radial and tangential cross-section dimensions of softwood tracheids for earlywood and latewood exhibit curves that are approximately similar in shape. However, the diameter increase is faster in earlywood, whereas latewood shows greater increase in the cell wall thickness (Stairs et al. 1966, Olesen 1977, Kibblewhite 1981, Saranpää 1985).

Typical increase in Norway spruce average tangential fiber diameter at breast height from pith to bark is shown in Fig. 21, based on studies of Olesen (1977). He found that tangential tracheid width, irrespective to position along the stem length, was about 15 µm in the first formed secondary xylem, wherefrom it increases with increasing ring number at first rapidly later only slowly to a width of 30–40 µm in outer sapwood. It is notable that, like in fiber length, the rate of increase for these two morphological properties is highest in within the first 10 to 30 growth rings around the pith, i.e. juvenile wood (see Section 2.7), levelling off after the transition to mature wood. The increment towards the bark is notably faster in the upper parts of the stem. Since also the average radial diameter of the tracheids increases with the same pattern, the number of fibers per unit volume of wood decrease rapidly with increasing ring number. The above discussed patterns of variation in Norway spruce are supported by many investigators (see e.g. Hartig 1898, Nylinder 1953, Stairs et al. 1966, Atmer and Thörnqvist 1982, Kucera 1994).

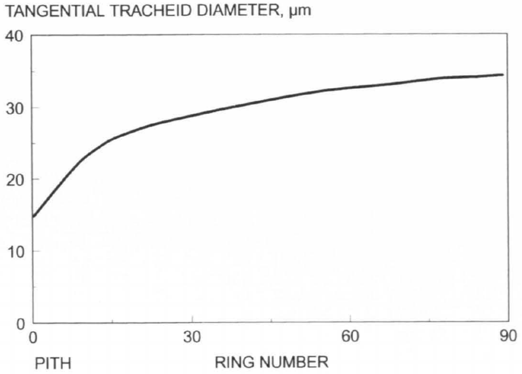


Figure 21. The relationship between the mean tangential tracheid diameter and ring number from the pith in four 90-year-old Norway spruces at breast height (Olesen 1977).

Only a very limited data is provided from the average wall thickness along the radius. Determination of such data is confused by the variation in latewood content However, studies made with numerous softwoods, all agree that wall thickness in latewood increases progressively from 15 to 70 percent, in successive increments at least up to 30 years of age (see e.g. Panshin and deZeeuw 1980, Haygreen and Bowyer 1989, Zobel and Buijtenen, van 1989). As both the cell wall thickness and the percentage of latewood tend to increase towards the bark, average fiber wall thickness is highest in the outer parts of an old spruce stem.

A small amount of studies have been made of cell diameter variation along the stem length. Early investigators, such as Hartig (1892, 1898), Bertog (1895) and Mork (1928), have supplied comprehensive data of radial tracheid diameter within specified annual rings and ring sections at various tree heights in spruce. Unfortunately, information about radial location of observations, in the stem cross-section, is uncomplete. According to Mork (1928), in a mature spruce stem, the average radial fiber diameter of a cross-cut is highest, approximately 35 µm, in the stump cross-cut, decreasing thereafter upwards the stem, being about 20 µm near the tree top. Similar findings have also been made by Nylinder and Hägglund (1954), and later by Atmer and Thörnqvist (1982), who found also that in the outermost growth rings the fiber diameter (tangential) is slightly highest at about 40 % height level. This is well in agreement with the study of France and Mexal (1980) for other spruce species (*Picea engelmannii*). They found for that both the average fiber length and radial and tangential cell diameters, in a specified growth ring, increased with increasing height to midbole, and then decreased with further increases in height.

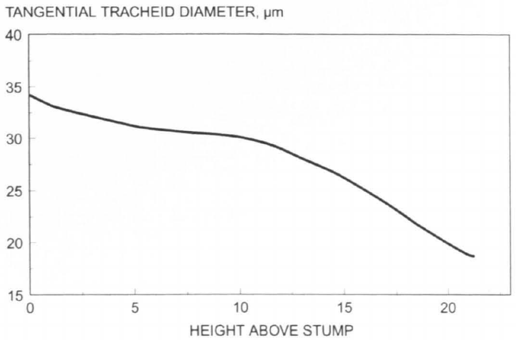


Figure 22. The average radial tracheid diameter in crosscuttings of Norway spruce stems at various heights of a stem. Drawn from Mork's (1928) data.

Cell wall thicknesses have been reported to vary with height in the trunk for some softwoods, but there is mostly controversial and incomplete data of the patterns of variation in this respect (Panshin and de Zeeuw 1980, Timell 1986). For instance, France and Mexal (1980) found cell wall thickness to vary independently of heigth in the bolewood of *Picea engelmannii* and *Pinus contorta*. Despite the incomplete and controversial information about variation of either cell diameter and especially cell wall thickness along the stem heigth, the decreasing pattern in both average cell tangential diameter and wall thickness is intuitively obvious due to radial variation in these properties. Because of this, spruce top logs have narrower and thinner-walled tracheids than butt logs, on an average.

As mentioned earlier, both fiber diameter and cell wall thickness are determined by genetical and environmental factors. Unlike in the case of fiber length, these relationships, especially with fiber wall thickness, are not very clear, or contradicting data exists. However, it is commonly known that fast-grown trees tend to have tracheids with larger tangential diameter, than slow-grown stems. Furthermore, the radial diameter in mature wood seem to be affected mostly by growth rate (Zobel and Buijtenen, van 1989). For Norway spruce, the average radial fiber diameter is found to be positively correlated with ring width, shoot growth, and rate of xylem increment (Mork 1928, Jalava 1952).

2.5.2 Influence of Fiber Cross-Sectional Dimensions on TMP Manufacture

As being stated earlier, both width of the cell and thickness of the cell wall are considered to be of prime importance on the quality of a paper product. Despite the above fact, other wood properties such as the length of fibers, wood specific gravity etc. have been historically considered to have more relevance in pulp and paper manufacture. It is known that the intrinsic strength of a single fiber is largely dependent on the cross-sectional wall area, i.e. fiber perimeter and wall thickness, ultrastructure of cell wall (fibril angle), and its chemical composition (Page et al. 1977, d'Clark 1985). Since the intrinsic strength of a single wood fiber is several times greater than that obtainable in a paper sheet, it is not known to which extent it is responsible for paper strength properties (Nordman 1990). Moreover, according to Shallhorn and Karnis (1979), mechanical pulps usually undergo tensile failure by fiber pull-out, so that fiber bonding, and not fiber strength, largely controls the sheet tensile strength.

Increasingly common technical term used to characterize wood and pulp fibers is the *fiber coarseness*, being a measure of relative fiber cross-sectional area (Britt 1965). Good correlations between fiber coarseness and pulp properties have been found when chemical pulps are being characterized (d'Clark 1985, Paavilainen 1993). However, since mechanical pulps are composed of not only whole fibers but also fines material, its use can be questionable, except for the long fiber fraction. Moreover, as can be intuitively concluded, two pulps with identical coarseness, but one having fibers that are considerably larger in diameter but have thinner cell walls vs. another pulp having smaller diameter fibers with thicker cell walls must have different bonding properties and form sheet with different strength and printing properties.

Unlike in the case of chemical pulps, no general correlations between fiber diameter or wall thickness, and pulp properties have been found in mechanical pulps, except when different wood species are compared (see e.g. Dinwoodie 1965, Jackson and Williams 1979, Hatton and Cook 1990, Corson 1991, Höglund and Wilhelmsson 1993). Therefore, most of the assumed impacts are purely qualitative in nature, or made from the basis of species comparison. Generally, fibers that are large in diameter and thick-walled, seem to be most defective for both pulp strength and printing properties. Because most of the lignin is still left in the cell walls, all mechanical pulp fibers are relatively stiff, do not swell and collapse to the same degree in paper making process than the chemical pulp fibers. It should be noted that the long fiber fraction consists of typically only one third of pulp's dry matter. However, it is shown that the poor flexibility of fibers, typical for the TMP long fiber fractions in comparison to other mechanical pulps, can be improved by mechanical and chemical means (Jackson and Williams 1979, Corson 1980).

It is demonstrated in numerous studies (Forgacs 1965, Corson 1979, Jackson and Williams 1979, Mohlin 1979, Laamanen 1983, Heikkurinen 1992 etc.) that in all mechanical pulps, not only the fiber morphology or share of different pulp fractions, but especially the quality of these fractions affect considerably pulp properties. In the light of foregoing, it is obvious that other factors than simply fiber dimensions or coarseness, affect pulp's properties. These factors include the proportion of fines material and external fibrillation of fibers, being mainly influenced by the applied specific energy and other process conditions, and not the fiber morphology .

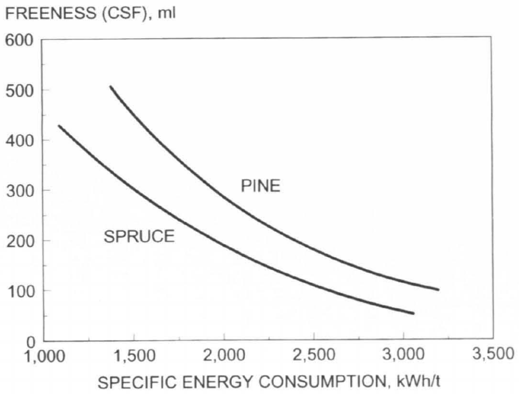


Figure 23. Refining energy in relationship with freeness (CSF) in TMP pulps made from *Pinus banksiana* and *Picea mariana* (Jossart et al. 1987). Wood with the coarsest fiber requires more energy per weight unit of pulp.

When the energy requirement *between different softwood species* for the manufacture of TMP is being considered, woods such as spruces, having small diameter fibers and thin cell walls, are favoured (Lindström et al. 1977, Kurdin 1979, Hartler 1985, Jossart et al. 1987, Härkönen et al. 1989, Quick et al. 1991, Harris 1993, Rudie et al. 1993 etc.). For instance, the results by study of Jossart et al. (1987), complement the results of many previous studies and indicate (see Fig. 23), that, in agreement with intrinsic fiber characteristics of wood and refining mechanisms, substantially more refining energy is required for jack pine (*Pinus banksiana*) compared to black spruce (*Picea mariana*). With the same average wood fiber length, jack pine have approximately 25 % thicker cell walls and greater fiber diameter than black spruce. Moreover, it was shown that as more energy is required to increase fiber fibrillation and flexibility, thicker-walled fibers are prone to fiber cutting. Similar results have been obtained for Norway spruce relative to pines (see also Lindström et al. 1979, Härkönen et al. 1989).

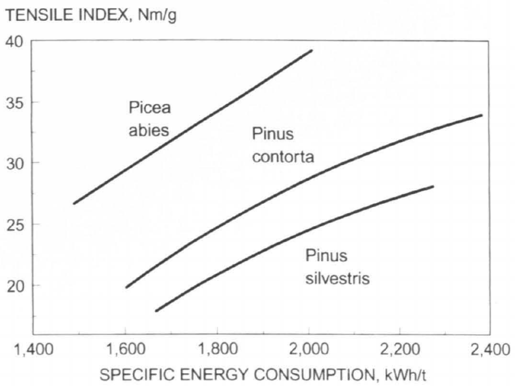


Figure 24. Tensile index vs. specific energy consumption of thermomechanical pulps made from three different softwood species. Spruce has the best and pine the poorest tensile index at the same SEC level (Härkönen et al. 1989).

In thermomechanical refining only a small portion of energy is required for fiber separation. The major portion of the total energy used, is needed to develop the fiber by breaking up the fiber wall and peeling off the outer and S_1-layer (Giertz 1977, Kurdin 1979, Hartler 1985, Karnis 1994). According to Kurdin (1979), thicker wall fibers require more energy to develop to the same degree. This is largely supported by Pearson (1990) and Hickey and Rudie (1993), who have found that thinner-walled fibers absorb energy more readily than thicker-walled fibers, this being a possible explanation to the above difference in specific energy consumption between.

When the above comparison is made *within a wood species*, the effect of fiber cross-sectional dimensions on between fiber morphology on pulp specific energy consumption is no more clear. It has been known for a long time for stone groundwood that wood with higher density, i.e. greater average cell wall thickness or high latewood content, gives generally pulp with better properties, but with same or decreased specific energy consumption (deMontmorency 1965). In several studies, within a softwood species, TMP from juvenile wood, typically having less coarse fibers, has consumed somewhat more energy than corresponding pulp from slabwood or other parts of the stem (Hatton and Cook 1990, Corson 1992, Hatton and Johal 1994). It is not known, why this happens, but possible explanation can be found from the mechanics of refining and significant differences in morphological, ultrastructural and chemical differences between juvenile and mature wood tracheids (see Section 2.7).

On the contrary, Corson (1983) refined thermomechanically *Pinus radiata* butt logs, second logs and top logs separately, finding that each of the two butt log samples consumed more power to reach a specific freeness than did any of the second or top log samples. Moreover, the high density sample consumed more energy than did the companion low density sample. It should be noted here that for spruces, for instance, the within-tree variation patterns of the fiber properties and wood density deviate considerably from those typical for radiata pine or southern pine species, thus, making the critical examination more difficult.

Some indirect information about the specific energy consumption as related to fiber cross-sectional dimensions of Norway spruce, can be found in Braaten et al. (1993). Namely, they refined different wood assortments, such as slabwood, thinnings, toplogs and butt/middle logs in laboratory scale, and found no statistically significant differences between any of these assortments. Even though data on wood properties were not provided, it can be assumed that the fiber cross-sectional dimensions vary closely with the patterns presented in previous section (Section 2.5.1).

When different wood species or fiber sources for thermomechanical pulps are considered in general, small fiber diameter equals improved printability, opacity and softness, whereas larger fiber diameter equals high bulk but reduced smoothness and printability. Furthermore, thick fiber wall is said to equal lower tensile, higher linting, and reduced smoothness. According to Giertz (1977), thinwalled fibers, like aspen, are flexible and collapse and form relatively well bonded and strong sheet, in *high-yield pulps*, that is TMP, for instance. On the contrary, stiff thick-walled fibers form a bulky and weak sheet. It is true, though, that the optical and surface quality disadvantage of high fiber coarseness can be offset to some extent by higher specific energy application in mechanical pulping and by selective treatment of the coarse fiber fraction, resulting in improved tensile, smoothness, porosity, and opacity (see e.g. Kurdin 1979, Kibblewhite 1981, Corson 1992, Harris 1993, Höglund and Wilhelmsson 1993).

Although mechanical pulp fibers are stiff and unflexible compared to chemical pulp fibers (see e.g Forgacs 1963, Giertz 1977, Malinen 1986), most slender fibers have the best bonding capacity at the same fiber length. In their study, where three softwood species, grown in Northern Finland, were compared in a pilot scale TMP manufacture, Härkönen et al. (1989) found that Norway spruce, with most slender fibers resulted in the highest tensile index at constant energy consumption and fiber length. Tensile index of lodgepole pine (*Pinus contorta*) fall in between that of Norway spruce and Scots pine, having the coarsest fibers at the same fiber length. The coarseness values at constant 1.3 mm pulp average fiber length were in the same order 0.25, 0.27, and 0.29 mg/m. Since the average fiber diameters for these three wood species were practically equal, cell wall thickness explained most of the differences in cross-sectional dimensions.

The above findings, obtained by Härkönen et al. (1989), are supported by Lindström et al. (1977) for TMP from Norway spruce and Scots pine, as well as Jossart et al. (1987), who made TMP trials with jack pine (*Pinus banksiana*) and black spruce (*Picea mariana*). In the latter study all strength properties, with the exception of tear index, were approximately 35 % inferior, either or constant freeness or energy consumption, to black spruce over the range investigated. The tear index of both species followed a complex behavior; it increased with refining energy at first due to better bonding and decreases subsequently due to fiber shortening with refining energy. They attributed the found differences in the pulp strength properties merely to coarser fiber of jack pine, mentioned before in this chapter. For the same reason, when standard refining conditions were applied, black spruce retained better their fiber length at a given freeness, this fact naturally contributing both the wet-web and dry sheet strength properties of spruce pulps.

Only a very limited data is provided from refining wood with varying fiber wall thickness or fiber diameter within the same wood species. One aspect that make these comparisons difficult is the existence of juvenile wood (see Chapter 2.7), which have smaller diameter fibers with thinner cell walls, but which deviate from mature wood fibers also in other respects (Hatton and Johal 1994, Corson and Kibblewhite 1986 etc.). In his comprehensive study on loblolly pine (*Pinus taeda*) wood properties in terms of laboratory-scale refiner mechanical pulp, McMillin (1969) found that burst, tensile strength, and sheet density were improved by using wood with narrow-diameter tracheids, but thick walls. Only narrow diameter was required to improve tear strength. However, the tracheid morphology of this wood species deviate from Norway spruce to such an extent that definitive conclusions cannot be made. By contrast, Stairs et al. (1966) pulped slow- and fast-grown Norway spruce in a laboratory refiner, and found that fast-grown variant, with larger diameter fibers and same wall thickness, gave superior pulp in terms of tensile, tear, and burst strength. Also sheet density and optical properties were better than in slowly-grown wood. Again, caution should be made when interpreting these results.

Cell diameter and fiber wall thickness both have their influence on paper surface and printing properties (see e.g. Wood and Karnis 1977, Hooper 1987, Corson 1992, Aspler and Beland 1994) This is especially the case in mechanical pulps, where the long fiber fraction typically contain stiff long fibers, with a low degree of fiber collapse. As already listed in Section 1.2, among the requirements of TMP, used for high quality wood-containing publication papers, such as LWC-, newsprint, improved newsprint and SC-papers, is low fiber coarseness for enhanced opacity, smoothness, and formation. This effectively refers to the fact, that intact mechanical pulp fibers, in the long fiber fraction, must achieve a high degree of fibrillation and maximum fiber collapse. Furthermore, a high degree of fiber collapse should result dimensionally stable printing surface, helping to minimise *fiber puffing* (or *fiber rising*) and *linting*.

According to Aspler and Beland (1994), fiber rising, sheet surface roughening and related surface disturbances occur when water comes into contact with mechanical printing papers. This problem is generally worsened in the presence of more mechanical pulp (especially long fibers), more shives, more thick-walled wood species, and more thick-walled fibers (i.e. latewood). When the degree of mechanical pulp fiber collapse is low, the paper tends to be prone to fiber puffing. However, a higher degree of mechanical pulp fiber collapse can be achieved only via high specific energy application (Kurdin 1979, Corson and Ekstam 1993, Höglund and Wilhelmsson 1993, Karnis 1994,) or selective chemical treatment of the long coarse fibers (e.g., alkaline-peroxide treatment of rejects) followed by refining, according to Harris (1993). Aspler and Beland (1994) have concluded that because of intrafiber stresses, the surface changes caused by paper processing, for instance calendering, are not permanent and fibers show a tendency to recover their original uncollapsed shape after water has been applied into the sheet at paper converting or printing. Figure 25 shows typical caliper for various wood-containing publication papers compared with fiber dimensions. Since the diameter of uncollapsed mechanical pulp fibers may exceed half the sheet thickness for SC-paper, it should be noted here, that fiber dimensions are of importance, when the surface properties are considered.

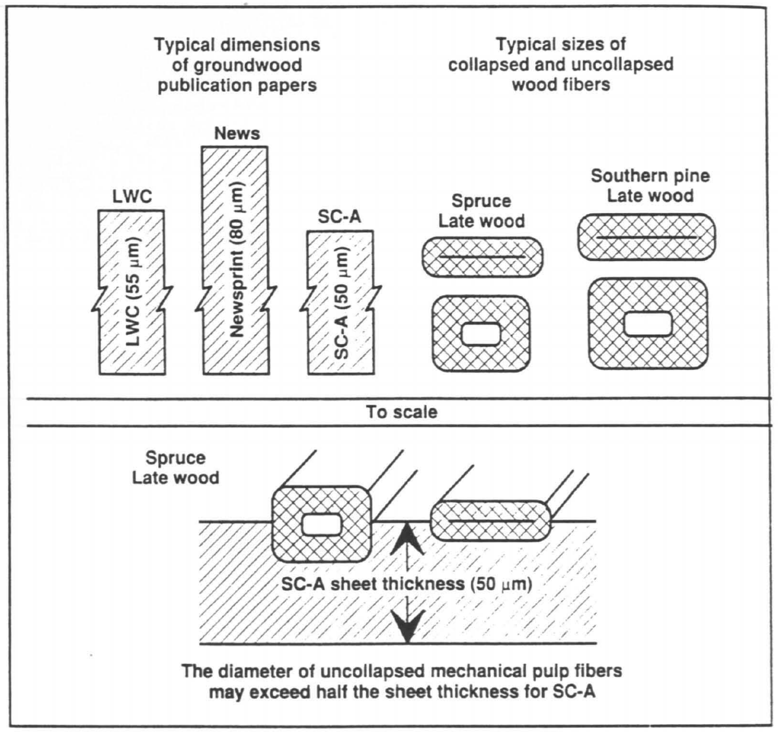


Figure 25. Typical caliper for various groundwood publication papers compared with fiber dimensions of Northern spruce and Southern pine (Harris 1993).

When TMP pulps that have different fiber size distribution are considered as a furnish for paper, it is true that smaller fibers or fibers with thin walls have more surface in relation to their mass. At least in theory, this would lead into better optical properties, i.e. better light scattering power in pulp. However, if the concept of juvenile wood fibers is excluded, no studies have been reported on the relationship of fiber cross-sectional dimensions and mechanical pulp optical properties within a same wood species (see e.g. Corson 1983, 1986a,b, Hatton and Cook 1990, Höglund and Wilhelmsson 1993, Hatton and Johal 1994). Optical properties in mechanical pulps, is a complicated function of the proportion and quality of different pulp fractions and sheet structure. According to Kubelka-Munk's theory, the light scattering power of a pulp increases as there are more free, light scattering surfaces present in a sheet, thus this being mainly a structural feature and independent of light absorption properties. Therefore, the fiber cross-sectional dimensions can determine only partially these properties, the main effect coming from the proportion of finer particles and their properties in pulp (Giertz 1977, Corson 1979). The processing conditions and the level of applied refining energy are the main determinants influencing the obtained brightness and opacity of TMP (Giertz 1977, Leask 1987a). In the light of foregoing discussion, it is obvious that the optical properties in mechanical pulps cannot be predicted directly from raw material fiber morphology.

2.5.3 Summation

Norway spruce has generally slender fibers, i.e. with narrow diameter and thin cell walls, being favourable properties, when different wood species are compared as a raw material for TMP. Although the within-tree or intra-tree variation in cell cross-sectional dimensions is not that great in spruces compared to pines, for instance, there is a distinct pattern of variation which occurs in the radial direction of the stem. Namely, in a mature stem the average fiber dimension increases from about 15 µm, nearest the pith, to about 35 µm, closest to the cambium. The average cell wall increases with a similar, but somewhat weaker pattern, towards the bark. Typically, the radial increase in average cell wall thickness can be from 2–3 µm to 4–5 µm. Although the longitudinal variation in fiber cross-dimensions within the same growth ring is neglible, it follows from the radial variation that topwood consists considerably thinner-walled and smaller-diameter fibers than for instance butt-log or saw mill chips.

Wood fiber cross-sectional dimensions, that is, fiber diameter and wall thickness, can have a striking effect on TMP strength, optical and printing properties as well as specific energy consumption, but the effects caused by these dimensions are less pronounced than in the case of chemical pulps. This is because only a one third of mechanical pulp material is consisted of whole fibers, and, irrespective to fiber morphology, all mechanical pulp fibers are relatively stiff. Since thermomechanical pulping process is purely a harsh, mechanical method where the wood matrix must first break down so that fiber separation, development of fiber bonding ability and fines creation can is possible to occur, the conditions of process are of greatest importance determining the final pulp properties. Between wood species, coarser fiber having thicker cell walls and larger diameter, is known to give TMP with poorer strength and printing properties, that is always achieved with elevated energy consumption. Within a wood species, such correlations have not been found yet. When comparison is made either between wood species or within a species, fibers with thick walls and large diameter are known to give generally poor sheet and printing properties. TMP optical properties are not principally determined by fiber dimensions.

2.6 Earlywood and Latewood

The existence of two distinctly different cell types – earlywood and latewood tracheids – cause the greatest variation in fiber morphology normally occurring within an annual increment. The thin-walled, large diameter earlywood (or springwood) cells formed at the beginning of a growth period function primarily as water and mineral transportation tissue, whereas thick-walled, narrow latewood (or summerwood) cells formed at the end of the season give mechanical strength to the stem, branches and roots of a living tree. At the very end of the season, when growth is extremely low, the latewood cells become flattened in the radial direction (see e.g. Sarvas 1964, Siau 1984, Zobel and Buijtenen, van 1989). Factors, internal and external, governing the formation of earlywood and latewood in softwoods have been discussed among others by Larson (1962, 1964, and 1969), McKinnel and Shepherd (1971) and Gardiner (1978). Several attempts to make exact definitions for the fiber types has been made, like those by Mork (1928a) and Wiksten (1945). However, it is not always clear into which category a single tracheid belongs, because the transition from earlywood to latewood can be gradual, like in Norway spruce. Following table (Table 5) shows average radial and tangential cross-sectional dimensions of earlywood and latewood tracheids in Norway spruce stemwood.

Table 5. Tangential and radial wall thickness, and tracheid diameter in earlywood and latewood zones of Norway spruce. All values in µm.

Tracheid dimension	Earlywood		Latewood	
	Tang.	Rad.	Tang.	Rad.
Wall thickness[1]	2.90	3.52	4.69	6.23
Diameter[2]	32.7	39.3	32.1	13.1

Sources: [1]= Ollinmaa (1959) and [2] = Fengel (1968)

Since latewood have considerably higher basic density than earlywood (see Chapter 2.2), latewood is several times stronger and stiffer than earlywood (Kennedy 1966, Laurent et al. 1993). Not only the fiber cross-sectional dimensions deviate between earlywood and latewood, but there are several anatomical differences. Namely, latewood fibers are recorded to be consistently about 10 % longer than earlywood fibers (Neergaard 1928, Helander 1933). There are smaller and fewer pits in latewood, especially in tangential surfaces. The number of pits varies from 50 to 300 in earlywood, with fewer pits in latewood (Stamm 1964). Earlywood fibers are very rich in bordered pits, whereas latewood fibers are almost completely lacking bordered pits (Jalava 1952, Eskilsson 1972). The above pore structure have its negative impact on the liquid conductivity and permeability of latewood fibers (Siau 1984).

In terms of chemical composition, it is known that earlywood fibers contain more lignin and less cellulose than latewood, because of the relative proportions of secondary wall and middle lamella in these wood tissues (Sjöström 1981, Fengel and Wegener 1989). Due to differences in the cell wall ultrastructure, the average fibril angle is about 5–10 degrees in latewood, and about 20–25 degrees in earlywood, making the former fiber type much stronger paper making fiber (Pillow and Luxford 1937, Tsoumis 1968, Page et al. 1977). It is quite clear from the foregoing that these two fiber types with distinctive characteristics, are given attention in pulp and paper making, especially the stiff and rigid latewood fibers.

2.6.1 Variation in Latewood Percentage

Although the average wood properties in conifers are important, the difference between earlywood and latewood can be so striking that one often needs to assess earlywood and latewood separately. According to Zobel and Buijtenen, van (1989), a good starting point is the evaluation of the proportion of latewood, which often denoted as *percentage of latewood* (by volume). It should be borne in mind that latewood percentage denotes, however, only the proportion of the xylem that meets the minimum cell-wall thickness (Mork 1928a,b) and gives no indication of the variation in wall thickness or fiber diameter within the two zones in a growth ring. Therefore, when wood is used for pulp and paper products the percentage of latewood can be of importance, not as a general indicator, but mainly via the properties of its fibers (Harris 1993, Paavilainen 1994).

Despite the criticism that has been expressed by various investigators of the unsuitability of latewood percentage as an indicator of wood characteristics in conifers, its use could still be adapted to the purpose, when a single species from a geographically restricted area is in question. In Norway spruce and some other conifers, the absolute amount of latewood is approximately constant irrespective to the ring-width. Therefore, latewood percentage has a strong negative apparent correlation with the ring-width. This is true at least at limited ring widths, from 0.5 to 2.5 mm, in mature wood of Finland-grown spruce (Wegelius 1939, Hakkila 1968, Saikku 1975). However, there are some contradictory results, according to which the latewood width in Norway spruce increases with increasing ring width (Klem 1957, Olesen 1976).

The average latewood percent in Norway spruce, grown in southern Finland is approximately 23 %, varying from 15 to 33 % between the stands. The latewood percentage of spruce increases towards the north, being averagely over 30 % in Lappland, the northernmost parts of Finland (Jalava 1952, Hakkila 1968). If the latewood percentage is determined on a weight basis instead of on a volume basis, the numerical values obtained would be naturally higher. It should be noted that the latewood percentage in most pines is higher than of spruce. In southern Finnish pine (*Pinus* *sylvestris*) the average latewood percentage is about 25 %, and many other pines, such as loblolly pine (*Pinus taeda*), may contain over 50 % of latewood (McMillin 1968, Gladstone et al. 1979).

Generally in softwoods, the percentage of latewood usually increases from pith to bark (see e.g. Jalava 1952, Zobel and Buijtenen, van 1989, Haygreen and Bowyer 1989). Hakkila (1966) has found that the percentage of latewood in spruce grown in southern Finland rises from about 15 % in the first five annual rings to about 20 % in ring number 20, whereafter the increase is slow ending up to about 24 % in ring number 60. This is supported by many investigators such as Mork (1928b), Olesen (1977) and Kuzera (1994). The following chart shows the pith-to-bark variation of latewood percentage in Norway spruce. The smoothed curve is drawn from Mork's (1928b) extensive data.

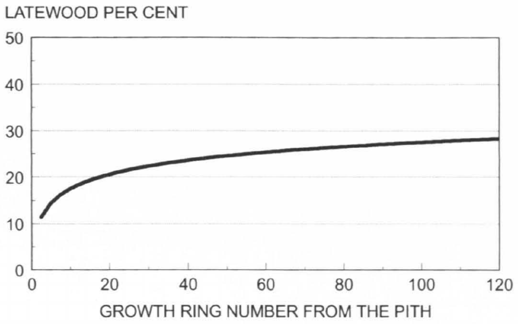


Figure 26. The pith-to-bark variation of the percentage latewood in Norway spruce according to Mork's (1928b) data.

As being intuitively clear from the tracheid formation process, discussed already in preceding sections (Sections 2.4 and 2.5), and in Figure 26, neither the latewood percent, nor the absolute amount of latewood, is same at all stem heights. The highest values for both variables are usually obtained at the butt level, wherefrom there is a decreasing pattern towards the tree top. Being so, the butt-logs from old, slowly-grown spruce stems have the highest latewood content, whereas toplogs and young stems have the smallest relative amount of latewood (Jalava 1952).

2.6.2 *Influence of Latewood on TMP Manufacture*

As earlywood and latewood fibers differ from each other to great extent, discussed earlier, their proportional occurrence naturally can be of decisive importance for wood, pulp and paper properties. The relationship between wood quality and paper properties has been the subject of several excellent reviews, such as by Dinwoodie (1965), Kibblewhite (1981) or Buijtenen, van (1967). However, the main emphasis has usually been in chemical pulps. The proportion of latewood and the fiber wall thickness in latewood cells are always considered as morphological factors with importance, in these studies. However, there are a lot of controversial data, referring that different pulps and wood species respond differently to processing. The general effects can be devided basically into two categories, namely, the impacts on the pulping process itself and the impacts on the paper end-product itself. What was discussed about the effects caused by thick-walled and coarse softwood fibers in TMP and derived papers earlier (see Chapter 2.5) apply naturally to a large extent to latewood, when a single wood species is being considered.

In terms of *chemical pulps*, the types of fiber, i.e. earlywood and latewood fibers, are known to have a strong effect on pulping as well as the paper end-products, these relationships being quite well established (see e.g. Gladstone et al. 1970, Zobel 1970, Page et al. 1972, Kibblewhite 1981, Paavilainen 1993). Due to basic differences between chemical and *mechanical pulps*, and their fiber component, it is obvious that the role of latewood in mechanical pulp and pulping differ dramatically from that of the former pulp type. It is known that all mechanical pulp whole fibers are relatively stiff, since most of the lignin has remained in the cell wall.

In fact, little consistent or conclusive data concerning the qualities of softwood mechanical pulp fibers, in terms of influences by latewood and earlywood, are available. This is especially true with thermomechanical pulp. However, the behavior of latewood fibers in refiner pulps and derived paper products has though awaked some very recent interest (Corson and Ekstam 1991, Laurent et al. 1993, Lai and Iwamilda 1993, Rudie et al. 1994). According to Kibblewhite (1981) all basic mechanical pulp processes (SGW, PGW, TMP, CTMP etc.) have a different effect on the fibers produced from the same wood source. Moreover, different wood species, or juvenile and mature woods cannot be compared by their latewood content, due to great differences in the fiber morphology. For instance, when compared at a certain latewood content level, the cell wall thickness of pulp made from sawmill chip fibers differs from that made of traditional roundwood assortments. The effects of earlywood-latewood ratio have therefore a relative nature and cannot be generalized.

Table 6. The influence of latewood percentage on the SGW pulps made from Norway spruce (Alftan, von 1958).

	Latewood percentage Low	High
Wood properties		
Basic density, kg/m^3	390	460
Growth ring width, mm	1.62	1.72
Moisture content, %	65	55
Latewood content, %	16.2	24.6
Pulp properties		
Freeness, ml	110	110
Bauer McNett fiber fractions		
R28 mesh, %	17.1	22.7
R48 mesh, %	19.2	20.7
R100 mesh, %	17.7	15.6
R200 mesh, %	13.9	11.7
P200 mesh, %	32.1	29.7
Breaking length, m	3950	4100
Bursting surface, m^2	23.3	25.7
Tearing surface, m^2	1.04	1.04
Specific energy consumption, kWh/t	1460	1460

According to study made at FPPRI by Alftan, von (1958), Norway spruce wood with a high latewood content gave groundwood pulp (SGW) of which quality deviated from that made from sprucewood having less latewood. The major findings are presented in Table 6.

As being apparent from the above, higher latewood content gave generally somewhat stronger pulp. Moreover, the proportion of long fibers was also greater and the proportion of fines material smaller, than in pulps of which raw material had more earlywood. When compared at a given wood volume, the consumed pulping energy was greater using wood with high latewood content, but no differences were found at constant pulp mass yield.

Unfortunately, no data exist from the above pulp's optical properties. However, earlywood fibers are known to generally contribute mechanical pulp optical properties, in terms of brightness and light scattering coefficent (Wilcox 1975, Suckling 1993). According to Wilcox, who has made extensive studies on brightness variation in both native wood and derived mechanical pulps, earlywood is brighter than latewood. This was despite the fact, that earlywood cells have a higher relative proportion of lignin in their cell walls, and therefore a higher light absorption coefficent, which, in turn, should actually result in poorer brightness. Nevertheless, the better initial brightness of earlywood was due to greater propotion of light scattering surfaces in earlywood. Although wood brightness as such will not be transferred to mechanical pulps, he suggested that almost 2 percent improvement in mechanical pulp brightness could be achieved by selecting the right wood source.

McMillin (1968a) prepared 96 loblolly pine (*Pinus taeda*) refiner mechanical pulps in laboratory conditions. He found no significant correlations between gross wood characteristics, such as basic density, latewood percentage or growth rate, and pulp properties, such as refining energy or sheet strength. Pulp properties were depended rather on the specific energy consumption or other independent variables, such as sheet density. However, of these wood variables, latewood content accounted though a large part of the variation in handsheet strength properties. As a conclusion from his comprehensive study, pulping low density wood, but with high latewood content gave systematically the best strength properties to refiner pulps. This is supported by his later study (McMillin 1968b). It is questionable to what extent these results can be applied to other wood species or mechanical pulping processes due to basic differences in between both wood and processes. Some of the his data is given in the following figures (Figs. 27–29).

Somewhat contradictory to the above, in New Zealand, a superior strain of radiata pine (*Pinus*

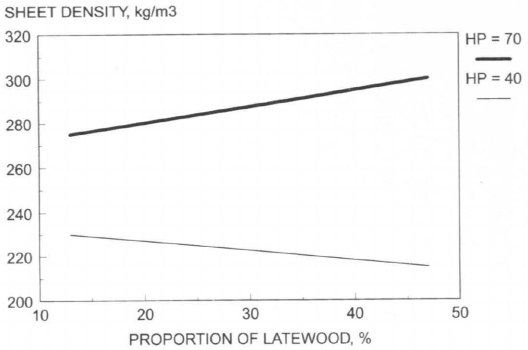


Figure 27. Loblolly pine refiner mechanical pulp sheet density as related to refining energy, either at 40 or 70 hp-day/air-dry ton, and proportion of latewood, according to McMillin (1968a).

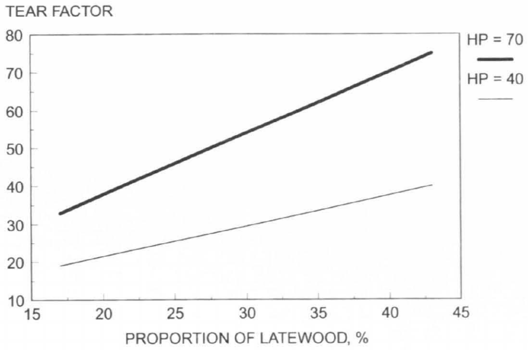


Figure 28. Loblolly pine refiner mechanical pulp tear factor as related to refining energy, either at 40 or 70 hp-day/air-dry ton, and proportion of latewood, according to McMillin (1968a).

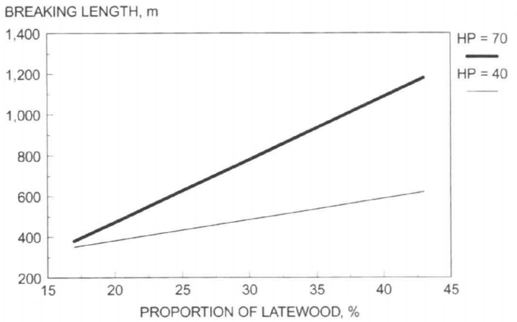


Figure 29. Loblolly pine refiner mechanical pulp breaking length as related to refining energy, either at 40 or 70 hp-day/air-dry ton, and proportion of latewood, according to McMillin (1968a).

radiata) has been developed, which has been found to give high-quality, low-energy TMP and CTMP pulps, compared to standard wood. Important factors are generally believed to include the lower latewood content and thin fiber wall of this Clone 55x wood (Corson 1994). The general wood properties of this species are closer to those of loblolly pine than Norway spruce. In a study by Stairs et al. (1966), it was found that when manufacturing laboratory-scale refiner mechanical pulp (RMP) from fast- and slow-grown Norway spruce, fast-grown trees gave clearly better strength and optical properties than did slow-grown trees. It should be noted that proportion latewood, both earlywood and latewood fiber widths, and wall thicknesses were somewhat greater in fast-grown wood.

In TMP refining, according to Hartler (1985), the two fiber types will be present in the mixture which constitutes the fiber mat to be strained in the narrow gap between the refiner plates. The earlywood and latewood fibers have different mechanical properties and are therefore expected to respond differently when exposed to mechanical forces in the narrow gap during high consistency refining of wood chips. Pearson (1984, 1990) in his studies, has discussed the fiber behavior during compression in the narrow gap and has pointed out that low-density wood is to be preferred because thin-walled springwood fibers are made flexible by the absorption of energy much more readily than thick-walled fibers. In that sense, wood having high latewood content is poorer raw materials for refining since they require more energy and the resultant pulp at the same freeness has a lower tensile index (Hartler 1985).

However, according to Lai and Iwamilda (1993), earlywood defiberization requires about 40 % more energy than the latewood in TMP made from Norway spruce. It should be pointed out that defiberizing energy is only a small fraction, about 10 to 20 %, of the total applied specific energy. Moreover, they suggested that the high density latewood fractures more readily than the more pliable earlywood. The fracture in the latewood takes place mainly in the S_1-layer while in the earlywood the fracture occurs across the double cell wall. They also concluded that at early stages of thermomechanical refining, i.e. at high freeness level, over 70 % of the fibers in long fiber fraction (R35) were latewood fibers. The enrichment of thicker-walled latewood fibers in the TMP long fiber fraction has been suggested also by Härkönen et al. (1989) and Laamanen (1983). According to Laamanen (1983), especially groundwood (SGW) pulps can have a very high content of thick-walled latewood fibers in their long fiber component as the result of the excessive breakage of the thinner-walled earlywood fibers during grinding.

In recent studies made by Rudie et al. (1994), Hickey and Rudie (1993) and Laurent et al. (1993), the behavior of earlywood and latewood in chip refining has been determined in loblolly pine. According to Hickey and Rudie (1993), the high latewood content and extreme difference in tensile strength and stiffness between earlywood and latewood in the southern pines creates a condition where the two growth zones are likely to behave differently in refining, and thus, in thermomechanical pulping. They concluded, after subjecting wood to cyclic compression, that the majority of the energy applied in the early stages of disk refining is absorbed by earlywood. A logical consequence of this preferential stress and energy absorption by earlywood is that it will disintegrate faster in the refining process than latewood. It has been shown in several studies that thicker walled latewood fibers provide much of the long fiber fraction in TMP, at least after low energy application (Hickey and Rudie 1993, Lai and Iwamilda 1993). However, Corson (1993) showed in his study with radiata pine TMP, that the relative proportion of latewood fibers in long fiber fraction (R30) decreased from 50 % to 15 % with successive refining of the whole pulp. Furthermore, he observed that less flexible, narrower diameter latewood fibers break more readily in refining than do the more flexible earlywood fibers. This is supported also by Kellison and Hitchings (1985), according to whom wood with a high earlywood proportion is commonly preferred for mechanical pulping because latewood tracheids are more often broken into stiff, pooly fibrillated fragments that compact poorly and yield weak, low-density, rough sheets prone to lint. Laurent et al. (1993) suggested that fractionating the earlywood and latewood fibers early in the refining process and refining the to fractions separately would improve the tensile index and specific energy relationship. In their experimental laboratory refining of loblolly pine, this was observed in the juvenile wood sample but not in the mature wood sample.

Even though the relationship, if there is one, between the latewood content, and thermomechanical pulping process and pulp properties is not known, or the findings in literature are contradictory, the effects of latewood fibers on paper properties should be quite obvious. Basing on a simple calculation, a mechanical pulp that has a high proportion of coarse and stiff latewood fibers, there are less fibers per unit weight. Irrespective to external fibrillation, latewood fibers have theoretically less bonding surface than earlywood fibers due to their smaller fiber width (Paavilainen 1993). A paper, manufactured from this pulp is expected to be bulkier than a paper which are mostly comprised of earlywood type fibers. However, it is not clear, to which extent the earlywood fibers collapse in pure mechanical pulps, since all mechanical pulp long fibers are stiff compared to chemical pulp fibers. Moreover, as stated by Hickey and Rudie (1993), who have largely studied the influence of latewood fibers in TMP, for instance, there have been many research papers on the influence of wood on mechanical pulping, some of them dating as far back as 1930's, but there is still not a clear understanding of how wood and wood fiber morphology affect mechanical pulping.

Höglund and Wilhelmsson (1993), who have studied the cross-sectional dimensions of wood and resulting pulp, point out that in TMP based wood-containing paper grades the long fibers constitute a key element of the sheet structure and therefore the share of earlywood and latewood fibers there might have a great impact on the outcome. Since the uncollapsed, stiff latewood fibers affect dramatically the smoothness of paper surface, the efficent treatment of this coarse fiber in refining is a major task of the pulping system. Namely, the thin and properly collapsed long fibers are certainly a valuable component in the sheet structure of all high quality printing papers, whereas thick, stiff and uncollapsed fibers are not (see e.g. Jackson and Williams 1979, Kartovaara 1990, Kurdin 1990, Harris 1993). This is of special importance in TMP systems for LWC grades, which typically have high printability requirements.

Therefore, a separation of these fibers for further treatment in the reject refiner is suggested (Höglund and Wilhelmsson 1993). However, present day screening equipment separate the fibers according to their length, but not cross-sectional dimensions.

According to Aspler and Beland (1994), *fiber rising* and *sheet roughening* and related surface disturbances in mechanical printing grade papers should be attributed especially to long, thick-walled latewood fibers. This has been discussed already in Chapter 2.5.2. The above defects occur when water comes into contact with paper sheet in printing or paper converting process. The fact that latewood fibers are prone to such disturbancies, is supported also by Corson (1992) and Kartovaara (1990), who pointed out that a latewood fiber, even when collapsed on the sheet surface, is still twice as thick as the coating layer in the average LWC sheet. Mohlin (1989) has also observed, that it is predominantly the thicker walled fibers, i.e. latewood fibers, that are poorly bonded in the sheet surface. Thus, they are either removed during offset printing, or roughened during offset printing and paper coating. Furthermore, Harris (1993), in his comparison of fiber raw material from northern spruces vs. southern pines, concluded that stiff, undeveloped and uncollapsed mechanical pulp long fibers, being largely latewood fibers, are mainly responsible for fiber rising, linting, poor surface strength and other surface disturbances in wood-containing publication papers. This is especially so in pulps made from southern pine species. The quality disadvantages, caused by coarse long fibers can naturally be offset by higher specific energy application and by selective mechanical and chemical treatment of the long fiber fraction, which should result in improved tensile strength, smoothness, porosity and opacity.

2.6.3 Summation

Within a wood species and a single coniferous tree, most of the variation occurring in fiber diameter and wall thickness can be attributed to the existence of two anatomically different types wood tracheids – earlywood and latewood fibers – being formed during the same growth period. Typically, radial diameter of Norway spruce earlywood is about 35 µm, whereas that of latewood fiber is only 13 µm. Tangential diameter of these fiber types is more constant, being about 30 µm in both. Average cell wall thickness vary from 2 to 4 µm, in earlywood, and 4 to 8 µm, in latewood. As already shown in preceding chapter (Chapter 2.5), the average radial diameters and wall thickness of these fibers increase with a distinct pattern from pith towards bark, the coarsest fibers being in outer wood of mature trees, close to the base. The average percent of latewood in Finland-grown *Picea abies* is 23 %, varying between the values 15 and 33 %. Highest content of latewood is found in the base of old, slowly-grown stems.

Despite that the physical, chemical and morphological properties of earlywood and latewood fibers deviate to such great extent from each others, no clear connection between the latewood content and mechanical pulp strength properties or power consumption, for instance, has been found yet. Presumably, there is a weak positive correlation with wood latewood content and pulp long fiber content. It can be stated that the literature is not very numerous and includes often contradictory results, what comes to the influence of latewood on TMP. Various mechanical pulping processes cannot be considered to respond uniformly to latewood. Moreover, different softwood species deviate very much in this respect, mainly due to their intrinsic fiber morphology. However, the presence of stiff and uncollapsed latewood fibers in paper end-products is known to have almost mere negative effects on its printing quality.

2.7 Juvenile and Mature Wood

Until recently, factors such as growth rate and its impact on important pulpwood properties, such as fiber length, has been incorrectly overemphasized. The main confusion has been in neglecting the anatomical phenomenon of having both *juvenile* and *mature wood* zones in a coniferous tree. The significance of juvenile wood was first recognized in the late 1970's as a steadily rising volume of wood raw material for the pulping industry in the southeastern U.S.A. comprised of young, fast-growing plantation wood, affecting the pulp quality. In northern commercial pulpwoods such as spruces, the above phenomenon is less pronounced, but still it is the most important factor causing variation in the wood properties from the pulp and paper maker's point of view. Within a few decades, a relatively great magnitude of data has been obtained from juvenile wood and its impact of pulping on the subject (see e.g. Boutelje 1968, Larson 1969, Zobel 1975, Yang et al. 1986, Thörnqvist 1990, Kibblewhite 1991, Corson 1991, 1994a,b, Kucera 1994, Hatton and Johal 1994).

In conifers, juvenile wood forms a cylindrical column surrounding the pith where cells have not fully matured. It is not yet clear, why juvenile wood is formed and the growth factors affecting it, but it is thought to result from the prolonged influence of the apical meristems (growing points) in the region of the active crown on the wood formed by cambium. As the tree crown moves farther upward in a growing tree, the influence of apical meristems on a given cambial region decreases, and mature wood fibers are formed (Larson 1969). Both juvenile and mature wood are produced simultaneously; mature wood at the base after cambium maturation and juvenile wood at the tree top by immature cambium, regardless of tree age (Zobel and Buijtenen, van 1989). The most recent findings on the subject has been made by Kucera (1994), in his extensive study of Norway spruce. He studied the radial variation patterns in wood properties, such as fiber length and fiber diameter, and found that a transition phase between the two types of wood tissue clearly coincided with culmination of the current annual height increment of the crown, however, this being in line with Larson's theory. In Norway spruce, the duration of the juvenile period is found to be from 20 to 30 years, whereafter subsequent growth rings towards the bark are mature wood (Boutelje 1968, Olesen 1977, Thörnqvist 1990, Kucera 1994)

Juvenile wood is not a single property, but a heterogenous tissue, where many wood properties change from pith towards cambium with varying speeds. Usually, these properties change very rapidly in distinct juvenile wood, nearest the pith, whereafter the change becomes smaller. This undefined zone between juvenile and mature wood is often referred to as transition zone. In distinctly mature wood, this change of properties continues towards the bark, but in much more gradual manner (McMillin 1968, Boutelje 1968, Zobel 1981, Megraw 1985, Kucera 1994). The wood properties that generally increase from juvenile wood to mature wood in conifers are: basic density, fiber length, fiber diameter, fiber wall thickness, latewood percentage, content of cellulose, wood strength. On the other hand, there is a decrease in longitudinal shrinkage, microfibril angle, wood light absorption, and lignin content (Haygreen and Bowyer 1989, Thörnqvist 1990). Some of these properties are dealt in detail in appropriate section of this study (see Sections 2.2, 2.4, 2.5 and 2.6). Cell wall structure and fiber dimensions are definitely the properties, that most severely deviate between the two wood tissues, these being also of highest interest for the pulp manufacturer. The above table (Table 7) shows some basic differences between important properties in Norway spruce juvenile and mature woods.

Table 7. Summary of some wood properties variation in Norway spruce juvenile and mature stemwood. Most of these wood properties are suggested to have importance for TMP.

Wood property	Juvenile wood	Mature wood
Basic density, kg/m^3	328–490	332–415
Fiber length, mm	1.28–2.70	2,80–4.29
Cell wall thickness, µm	0.80–4,6	2.10–7.53
Fiber diameter, µm	15.0–28.5	29.3–39.7
Fiber stiffness, $Nm^2 \cdot 10^{-12}$	0.24–0.34	1.3–2.4
Microfibrillar angle,	19.2–54.0	4.0–33.0
Longitudinal shrinkage, %	1.78–2.50	0.29–0.47
Lignin content, %	28.0–30.8	26.1–28.2
Cellulose content, %	38.1–40.3	40.2–42.7
Fiber coarseness, mg/m	0.160–0.210	0.260–0.310

Sources: Lönnberg et al. (1991), Harris (1993), Höglund and Wilhelmsson (1993), Kantola and Seitsonen (1969), Stairs et al. (1966), Ilvessalo-Pfäffli (1977), Jirjis et al. (1994), Tyrväinen (1993), Brolin and Noren (1993).

2.7.1 Variation in Juvenile Wood Content

According to Boutelje (1968) who has studied Norway spruce juvenile wood, in a young single tree of 20 years of age, the *proportion of juvenile wood* can be from 40 to 80 %. Correspondingly older trees (up to 80 years of age) measured on breast height, consisted of less than 10 % and in their tree tops, from 10 to 30 % of juvenile wood.

Practically, the maximum content of juvenile wood, volumetric or weight, always appears in the youngest trees and especially in tree tops, also in older trees. The diameter of juvenile core varied from 2 to 10 cm, depending on growth rate. Conception of the juvenile-wood as a cylindrical or conical zone in a tree stem is though practically useful but too simple. First of all, this zone is not evenly shaped and secondly its boundary does not follow the growth ring vertically. In the tree top, actually all growth rings may contain juvenile fibers, but lower the same year's growth rings are located farther from both pith and top and thus outside this zone (Thörnqvist 1990). Figure 30 shows schematically the juvenile wood core in Norway spruce stems (see Boutelje 1968, Hatton and Johal 1994).

It should be noted here that for many commercial pine species growing in favourable climate conditions, the content of juvenile wood is considerably higher in pulpwood normally arriving the mill. For instance, Kellison and Hitchings (1985) has reported that loblolly pine (*Pinus taeda*) pulpwood of as young age as 15 years, contained 15 % juvenile wood, whereas in stems of 40 years of age, as much as 75 % was juvenile wood. In this case, the high juvenile wood proportion is due to extremely fast diameter increase in the early years of growth, which, in turn, results in the fact that stems are of harvestable size younger. This is despite the fact that the formation of juvenile wood terminates at about 10 years of stem age in these pine species, whereas this in Norway spruce takes place much later, at about 25 years of stem age (Larson 1969, Zobel et al. 1973, Brazier 1985, Kucera 1994).

2.7.2 *Influence of Juvenile Wood on TMP Manufacture*

Unlike the chemical pulps, where juvenile wood is generally disfavored because of its many product and process characteristics inferior to pulps from mature wood, there are several reports emphasizing the opposite for some mechanical pulp properties. However, there has been a special emphasis on New-Zealand grown radiata pine (*Pinus radiata*) and southern pines, such as *Pinus taeda* grown in the southeastern U.S.A (see e.g. McMillin 1968, Kibblewhite 1981, Harris 1981, Corson 1983, 1991, 1994a, 1994b, Kellison and Hitchings 1985, Corson and Kibblewhite 1986, Corson and Richardson 1986, Murton and Corson 1992). Mature wood in these species consists of extremely large, thick-walled fibers with negative influence on mechanical pulp properties. Except for radiata pine, studies are few in number, where juvenile and mature woods are compared in terms of thermomechanical pulping. Some indirect data on the juvenile vs. mature wood TMP from Norway spruce, can be obtained from Braaten et al. (1993) laboratory-scale refining, where e.g. first-thinnings wood and butt log were refined separately. However, an increasing number of studies has appeared only recently dealing also with northern pulpwoods in this respect, among them Norway spruce (see e.g. Hatton and Cook 1990, Tyrväinen 1993, Hatton and Johal 1994, Jirjis et al. 1994). Before this, the effects of juvenile wood were explained by other wood factors, such as basic density or fiber length.

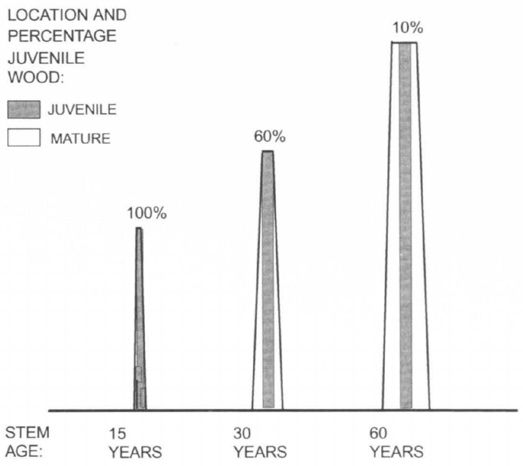


Figure 30. Typical average contents of juvenile wood in spruce at different stem ages (Boutelje 1968, Hatton and Johal 1994). A schematical drawing.

It is true that in Scandinavia, the juvenile wood content in pulp mill's raw material mix is typically low, being usually less than 10 %. For instance, sawmill chips contain practically no juvenile wood. But occasionally, when small diameter pulpwood is extensively used as furnish, it can be relatively high also in the case of spruce mechanical pulping. The biggest source of juvenile wood containing raw material is wood from young thinnings or tree tops. In such assortments, irrespective to the wood basic density, the yield of TMP per green volume of wood is always few percents lower compared to mature wood assortments. This effect comes mainly from higher content of bark and knotwood, especially in tree tops.

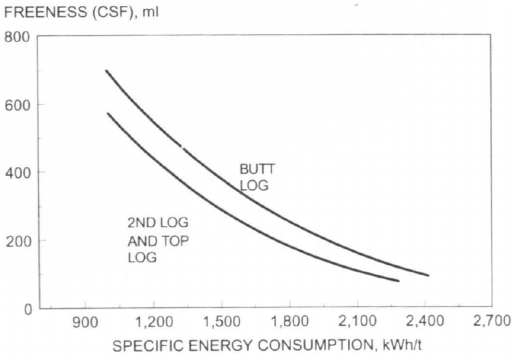


Figure 31. Freeness vs. power consumption of *Pinus radiata* TMP pulps made of butt logs, second logs and top logs (Corson 1983).

Main differences between the two wood types and thus concerning their relevance in mechanical pulping and pulps' can be attributed to their fiber morphology, due to considerably smaller scale of juvenile fibers. It is intuitively clear, that irrespective to what is the main mechanism in fiber separation and development in mechanical pulping, the juvenile and mature wood must respond in differently due to differences in fibril orientation of the S_2-walls, chemical composition, smaller fiber size, etc. This area is still undiscovered. Differences in chemical composition and cell wall ultrastructure must be less important than particle morphology, but might still have some impact on pulp bonding potential and optical properties, if fines and exposed fiber surfaces are composed in a different way. Heikkurinen (1992) points out in her recent literature review on the characteristic of TMP particles, that actually there has been very little research on the chemical and physical properties of fines particles and their relation to the original fiber type and source.

In mechanical pulping, only small portion of total energy applied is used for fiber separation. The majority of that energy is needed to develop the fiber by breaking up the fiber wall and peeling off the outer and S1-layer (Giertz 1977, Kurdin 1979, Karnis 1993). When refined thermomechanically to the same freeness level, juvenile wood needs somewhat less energy than mature wood, at least according to some investigators (see e.g. Corson 1983, Brill 1985, Tyrväinen 1993). Figure 31 explains Corson´s (1983) findings in radiata pine (*Pinus radiata*) TMP. The easy conclusion, that wood density alone controls the energy consumption in thermomechanical pulping, was clearly disproved by Corson in his later study (1991). He showed that wood density was of secondary importance to wood type, and suggested deductively that it is the characteristics of fiber which influence the behavior of juvenile and mature woods in refining.

However, being not in line with the above, there are findings made with various softwoods showing that juvenile wood, irrespective to wood density, might consume the same or about 10 % more energy than mature wood when refined to a constant freeness (Hatton and Cook 1991, Sundblad 1992, Braaten et al. 1993, Rudie et al. 1993, Hatton and Johal 1994). For instance, Braaten et al. (1993) in their small scale study of Norway spruce, found no significant difference in TMP power consumption between juvenile and mature wood type of assortments. The foregoing discussion suggests that there is differences between wood species and points out the great heterogenity of wood as a raw material.

When different TMP particle fractions, i.e. Bauer McNett fractions, are being considered, no dramatic differences in the proportions of fines fractions, between juvenile and mature wood TMP pulps have been found, if refined to same freeness (see e.g. Corson 1983, Brill 1985). Namely, in TMP pulps produced from both juvenile radiata pine and Scandinavian spruce as raw material, the proportion of fines fraction has been observed to be approximately the same or only slightly higher from juvenile wood. However, there is always a lower amount of long fibers, which is usually accompanied with an elevated content of fines. For instance, in Brill's (1985) study, TMP from mature type of Norway spruce wood, gave approximately 10–25 % higher long fiber content (R30) than juvenile type of wood. This is largely explained by the lower initial wood fiber length distribution yielding shorter average fiber length in juvenile wood pulps.

As a general trend, juvenile wood gives weaker mechanical pulp and TMP than mature wood. The impact of shorter average fiber length is obvious: it results directly to lower tear strength and in most cases lower tensile strength too at the same freeness level. In the above mentioned study by Brill (1985), of Norway spruce TMP, topwood pulp, consisting largely of juvenile fibers, gave on an average 23 % lower tear and from 0 to 18 % lower tensile index, than slabwood pulp, when determined at constant 140 ml freeness (CSF). Irrespective to consistent differences found in tear strength between juvenile and mature types of mechanical pulps, it is commonly known that pulps of juvenile fiber at lower freeness level can result to the same tensile and same or even higher burst strength to mature wood in standard pulping conditions (see e.g. Corson 1983, Kellison and Hitchings 1985, Braaten et al. 1993, Hatton and Johal 1994). In the case of tensile and burst strengths, the pulp bonding properties must be more important than the fiber length factor. TMP bonding properties are determined mainly by applied energy and refining conditions.

In mechanical pulps, there exists a close relationship between fines content, sheet consolidation and tensile strength. Generally, high sheet density is considered as indication of good bonding of pulp particles (see e.g. Corson 1979, Mohlin 1979, Shallhorn and Karnis 1979, Lindholm 1981). Further refining always increases the sheet density, because smaller and finer particles form denser sheet. According to Giertz's studies (1977) an important factor also for TMP pulps is the fiber wall thickness. Thin-walled fibers form relatively well bonded and strong sheet whereas stiff thick-walled fibers, like the latewood fibers, form a bulky and weak sheet. Since fibers in mature wood are known to be several times stiffer than juvenile fibers (Boutelje 1968), juvenile type of fiber could contribute good sheet consolidation. However, TMP from mature wood pulps is found to give somewhat (5–15 %) denser sheet than pulps from juvenile wood, when refined to constant freeness level (see e.g. Corson 1983, 1991, Brill 1985, Braaten et al. 1993, Hatton and Johal 1994). The above refers to deviation between the quality of fibers and fines in these pulps, resulting from physical and chemical differences between the two wood types. Again, no definitive conclusions can be made here.

It is widely known, that young Norway spruce stems or logs produce higher pulp brightness and optical properties than old wood (Nyblom 1979, Brill 1985, Braaten et al. 1993). There are several reasons for that, but since none of the parts of spruce stem does contain noteworthy amounts of colored extractives or other components, the main effect should be attributed to higher scattering power in juvenile pulp fractions. In most studies, regardless of whether the comparison is made on the basis of their freeness, sheet density, power consumption, or fines content, the TMP pulps of the toplogs or thinnings i.e. consisting largely of juvenile wood fibers, have superior brightness and scattering coefficents to those of mature fiber based pulps (see e.g. Corson 1983, Corson and Richardson 1986, Richardson et al. 1992, Braaten et al. 1993, Hatton and Johal 1994). For instance, Corson (1983) found radiata pine juvenile wood TMP at CSF 100 ml to give almost 10 % better light scattering index, than the pulp made of slabwood (Corson and Richardson 1986). In the former pulp, the ISO-brightness was 7 % higher. Figure 32 shows the scattering coefficent as a function of freeness in radiata pine TMP.

Corson and Kibblewhite (1986) determined the characteristics of fines particles of TMP made from either juvenile or mature woods. He found that the fines in the mature wood pulp had much more better bonding ability than those from juvenile wood pulp. Thus, more free light scattering surfaces remained in the latter pulp, partly explaining the good optical, but poor strength properties of juvenile wood pulp. It should also be noted that when coniferous juvenile wood is used as TMP raw material, the pulp fiber fractions can comprise of at least the double amount of single fibers (with thin walls) per weight unit and thus greater specific surface, compared to mature wood. This could partly explain the higher light scattering power of mechanical pulps made from juvenile wood. Interestingly, juvenile wood mechanical pulps produce better optical properties despite the higher light absorption of juvenile wood and pulps made from it. This fact naturally impairs its brightness potential (Wilcox 1975, Lee 1990, Suckling 1993).

Most pulping studies of the subject has concentrated on explaining pulp strength and optical properties, but no studies have been made especially on the printing properties of juvenile wood TMP compared to mature wood pulps. It could be expected that juvenile wood would give good printing properties for paper, since it has smaller fiber dimensions than mature wood (see also Section 2.5). On the printing properties generally, it can be said that smaller fiber diameter, as juvenile fibers are, equals improved printability, opacity and smoothness. According to Harris (1993), who have compared northern spruces and southern pines as a mechanical pulp raw material, juvenile type of fiber is generally favored for mechanical pulp component in wood-containing printing papers, and especially LWC paper, if printability is being considered. This is also supported by Corson (1992), who have largely studied the preferred characteristics of wood-containing printing papers, as related to fiber type. No studies has been published, whether juvenile spruce wood yields to TMP pulp with high linting tendency, for instance.

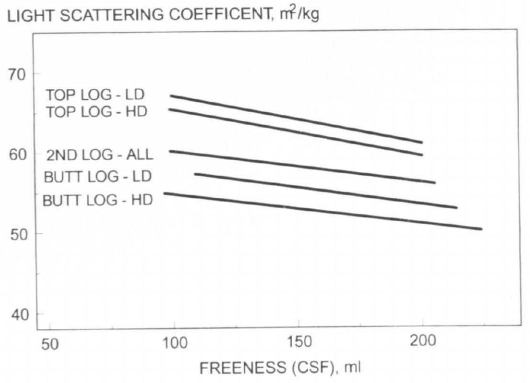


Figure 32. Scattering coefficent vs. CSF freeness (Corson 1983) in radiata pine TMP from toplogs, the second logs and buttlogs. (hd = high and ld = low original wood density)

2.7.3 Summation

The stem of a coniferous tree may be divided into two regions – juvenile and mature woods – on the basis of fundamental differences in the wood and fiber properties. In Norway spruce, juvenile wood core consists of approximately the first 20–25 growth-rings around the pith. Juvenile wood is thought to be formed by a young cambium in the region of the active crown, whereas in the lower part of an old stem, only mature wood tracheids are formed. It naturally follows, that young trees and also tree tops of older trees are purely juvenile wood. However, unlike in pulpwood in many southern regions, the content of juvenile wood is generally low, about 10 %, in the pulpwood used in Finland, since for instance sawmill chips contain only mature wood fibers.

Occurrence of juvenile wood causes the greatest variation in wood and fiber properties within a softwood tree. All of these properties change rapidly from pith towards the transition zone, whereafter the change is more gradual, and mature wood is formed. In juvenile wood of Norway spruce, the average length of fibers in juvenile wood is only about 1.0–2.5 mm, whereas those in mature wood are generally 2.5–4.0 mm. Corresponding figures for tracheid wall thickness are 1.0–4.5 µm vs. 2.0–8.0 µm, and 15–28 µm vs. 29–39 µm for fiber diameter. The microfibril angle of fibers decreases dramatically from around the pith to mature wood. This leads into a fact that juvenile wood fibers are weaker and prone to shrink longitudinally. Juvenile wood is known to have less latewood fibers than mature wood. Moreover, the content of lignin is 5–10 % higher and that of cellulose correspondingly lower, in juvenile wood.

Generally, the concept of juvenile wood and, especially, its influence on wood pulping, has been largely regocnized only a few decades ago. Basing on a limited number of studies, juvenile wood is known to produce up to 30 % poorer tear strength and same or even 20 % poorer tensile strength, than TMP from mature wood, at constant freeness. This is largely due to smaller long fiber content in juvenile wood pulps. On the other hand, pulp optical properties are excellent in TMP. Namely, pulp brightness can be expected to be about 10 %, and light scattering coefficent, which gives good opacifying properties for paper, even more than 20 % better in TMP made from juvenile type of wood. TMP from juvenile wood is expected to produce somewhat better printing properties. No clear pattern for TMP specific energy consumption at a constant freeness level has been found when juvenile and mature woods are compared. The differences in pulp strength and optical properties cannot be explained only with the proportions of different fractions or fiber size. Therefore, it is suggested that the fiber ultrastructure has a definitive role in this respect.

2.8 Heartwood and Sapwood

Formation of *heartwood*, occurring in most wood species, is a physiological process leading into well documented physical and chemical changes in that wood tissue. Unfortunately, for the pulp mill, these changes almost always interfere with conventional wood pulping and bleaching (Parham 1983a, Bierman 1993). In softwoods, heartwood is defined as the center portion of the stem where all the cells are dead for genetic reasons. Since the longitudinal tracheids, i.e. fibers, die during the cell lignification process, within the same growth season as they are formed, the above definition primarily refers to the parenchyma cells. Wood in young trees, and outside this heartwood zone in older trees denoted as *sapwood*, as it is capable of conducting "sap" in a living tree (see e.g. Siau 1984, Wagenführ 1984, Timell 1986).

The chemical, cytological, and physiological changes associated with the transition of sapwood into heartwood have been reviewed for instance by Hugentobler (1965), Ziegler (1968), and Hillis (1968a, 1968b, 1987). Several hypotheses of this "aging" phenomenon has been suggested, however, no commonly accepted explanation of the causes for heartwood formation and the exact mechanisms involved, has been presented to date. Transformation of sapwood to heartwood in Norway spruce, grown in southern Finland, commences averagely at about 30 years of age or less, while in northern parts of the country this age is approximately 70 years (Jalava 1952, Ilvessalo-Pfäffli 1979).

Heartwood is not a single wood property or not even a combination of certain properties, but each wood species deviate considerably in term of their heartwood characteristics. Unlike in genera *Pinus*, *Larix* or *Pseudotsuga*, Norway spruce among other members of *Picea* spp., have no colored heartwood, but have a distinct difference in moisture content between heartwood and sapwood, being in these wood tissues approximately 30 % and 60 %, respectively (see Section 2.3). Moreover, in majority of conifers, the formation of heartwood is accompanied by accumulation of a large amount of extractives in that wood tissue (Mayer-Wegelin 1955). For instance, Scots pine sapwood typically contains about 3 % (acetone) extractives, whereas the heartwood have approximately 5 % these substances (Section 2.10). Inner butt sections of old pine logs can have as much extractives as 25 % of weight. In Norway spruce heartwood the content of extractives is about the same or even lower than in sapwood, varying from 1 to 2 % in stemwood (Hakkila 1968).

It should be noted that transformation of sapwood to heartwood have no impact on tracheid morphology in that wood tissue. However, anatomical changes in cell wall structure, i.e. *pit aspiration*, take place during heartwood formation, affecting the pulping properties of such wood. In conifers, pits are the only intercellular channels for conduction of liquids in tracheids. During heartwood formation, or when wood is dried below the fiber saturation point (FSP), the pit membrane in bordered pits seals the aperture stopping effectively the flow of liquids through the pit (see e.g. Hartig 1901, Hart and Thomas 1967, Bauch et al. 1968). This phenomenon is known to be very pronounced in spruces, affecting the permeability of such wood and its fibers (Siau 1984, Beauford 1991, Bierman 1993).

2.8.1 Variation in Heartwood Content

With a special reference to pulping industry, the only valuable method to estimate the amount of heartwood is to define its volume proportion in roundwood (Ilvessalo-Pfäffli 1977). When expressed as per cent, this definition is often referred to as the *heartwood percentage*. Average values for spruce pulpwood in Finland has been obtained by Bruun (1967), for instance. According to his survey, the average heartwood content varied between 20 and 30 % in southern Finnish spruce pulpwood. Hakkila (1970), in his study of the properties of spruce saw logs used as pulpwood, found the average heartwood content in bolts from 27 truck loads arriving to a southern Finnish pulpmill to be 33.5 %. Since his material contained also butt sections of large trees, this value can be considered somewhat high for normal pulpwood (roundwood). Generally, the heartwood percentage in spruce pulpwood is clearly higher than that in pine at constant stem age or diameter (Table 8). Moreover, as will be shown later, the average heartwood percentage has a strong dependence on the geographical location of forest stand in Finland (Bruun 1967).

Table 8. The average content of heartwood in Finland-grown *Pinus sylvestris* and *Picea abies*, as a function tree age. The determination of heartwood was made at stump height of a tree (Heiskanen 1970).

Tree age, years	Heartwood content, % *Pinus sylvestris*	*Picea abies*
60	21	36
80	36	44
120	41	55
160	52	62
200	54	63

However, average heartwood percentage does not always serve the purpose, since the amount of heartwood varies greatly depending on tree height, tree age and growth rate in a conifer stem. Thus, knowledge of this variation is most often needed in terms of various pulpwood assortments. In conifers, the average proportion of heartwood is known to vary directly with tree age (Tamminen 1964, Yang and Hazenberg 1991, 1992). As already discussed, the formation of heartwood begins at a certain age, however, its boundary does not follow a specific growth ring in a stem. Consequently, young stems and tree tops have no heartwood, while in older trees, the diameter and height of the core continue to increase throughout the life of a tree, once its formation has been initiated. Generally, in a single stem the content of heartwood is highest at the base, wherefrom decreases towards the top (Hartig 1898, Tamminen 1964, Hakkila 1968, Koivuniemi 1992 etc.). However, in many northern softwoods, the highest heartwood percentage is not exactly at stump height, but somewhat higher. In Norway spruce, the highest value for the heartwood percentage is usually found at about breast height of a tree, whereas in Scots pine this culmination point is somewhat higher, corresponding to 20–30 % of the tree height (Ericson 1966, Hakkila 1967, Tamminen 1964, Uusvaara 1974). From this height on up to the crown the heartwood percentage decreases, as shown for spruce in Figure 33.

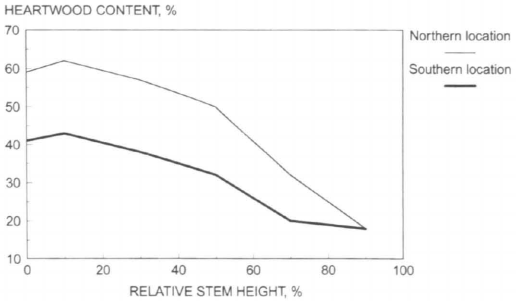


Figure 33. The average heartwood content, expressed as diameter percentage of the heartwood zone, in Norway spruce stands located in northern and southern Sweden (Tamminen 1964). It should be noted that the average tree age in the northern location was 113 years, whereas that in southern location was lower, only 61 years.

As being apparent from Fig. 33, the heartwood content in spruce pulpwood arriving the mill, depends on the geographical location. The geographical variation of the heartwood content of pulpwood in Finland has been studied for instance by Bruun (1965, 1967) and Hakkila (1968). Highest average values are found in northern parts of Scandinavia, even though the formation of heartwood starts at a later age in the north than in the south. This is a direct consequence of the slow growth rate and great age of trees, but also of genetical differences. Since the volume of heartwood increases faster than the volume of stem, older stems have relatively more heartwood than younger stems (Werberg 1930).

It has been shown in numerous studies, that slow growth rate in softwoods results in high heartwood content (Trendelenburg and Mayer-Wegelin 1955, Tamminen 1964, Hakkila 1968, Lassen and Okkonen 1969, Yang and Hazenberg 1991, 1992). The following table (Table 8) shows the dependence of heartwood content on tree age in Norway spruce and Scots pine according to Heiskanen (1970). In practice, the effect of growth rate on the content of heartwood in spruce, can be subdivided into two statements. Namely, at constant stem diameter, older trees have generally higher heartwood percentage than younger trees, while at constant tree age, fast grown trees (large diameter) have higher heartwood percentage than their slower-grown counterparts (Tamminen 1964). It should be pointed out that results contradictory to above exist (Yang and Hazenberg 1991, 1992, Koivuniemi 1992).

The effect of growth rate on the heartwood content is often related to site, stand and tree factors. Namely, within a softwood species the amount of heartwood is directly related to dominance of the tree in the stand, with the more vigorous trees having the smaller core of heartwood (Lassen and Okkonen 1969, Yang and Hazenberg 1992). According to Trendelenburg and Mayer-Wegelin (1955), in Scots pine and Norway spruce, trees with small crowns or trees grown in poor sites have a relatively high heartwood content. However, somewhat contradicting results has been obtained by Bruun (1965), who found that better site resulted in higher heartwood content in Norway spruce.

2.8.2 *Influence of Heartwood on TMP Manufacture*

Since heartwood is not a single wood property, that can be easily specified, like fiber length or basic density, its influence on pulping should be mainly evaluated via the properties it typically possesses. However, it is often difficult to consider the effects caused by heartwood alone, since all conifers show systematic from-pith-to-bark variation in wood anatomical properties, of which influence in most cases outperform the heartwood effect. The main effects of heartwood in Norway spruce, in terms of mechanical pulping, could be expected to result from its low moisture content and reduced permeability to liquids (Hattula and Mannström 1981). The effects of both wood moisture and extractives content in TMP manufacture, are dealt in detail elsewhere in this study (Sections 2.3.2 and 2.10.2), and are referred here only if directly related to heartwood content.

From the point of view of *chemical pulping*, sapwood and heartwood behave like different tree species. In pulping processes where chemicals are used, with reduced permeability, heartwood is also not as easily penetrated with pulping liquors, and the overall result can be large amounts of knotter and screened-pulp rejects. In Finnish pulpwoods, the above is true especially with the acid sulphite process (Bruun 1965). However, as stated by Hillis (1962), even with alkaline cooking liquors, it can be difficult to cook those wood species that have even ten times more extractives in heartwood than in sapwood, irrespective to the permeability differences (e.g. *Pinus banksiana*, *Pseudotsuga menziesii*). With such woods there are also attendant problems mechanical-type pulping processes and in pulp bleaching (Tay and Manchester 1981). Moreover, Back (1969), who has extensively studied the "pitch" problem in pulping with respect to wood anatomy, found that the extractives components found inside the tracheids from heartwood are the least accessible by sulphate and sulphite pulping systems. For instance, 10 % of extractives found in Nordic spruce sulphite pulp, were located inside the fibers which originated from heartwood.

In *mechanical pulping*, the presence of heartwood is most decisive in stone grinding-based processes, such as groundwood (SGW) and pressure-groundwood (PGW). This can be easily understood, since these processes utilize only roundwood bolts. It is known, that heartwood gives generally poorer groundwood than sapwood (Leask 1987a). There are a small number of experiments, where sapwood and heartwood has been ground separately. Table 9 shows the results basing on a study made by Alftan, von (1958).

It is apparent from the above study, that sapwood gives generally better strength properties and higher long fiber content for groundwood pulp than heartwood. In this case, the specific energy consumption needed to pulp sapwood into a same freeness level was somewhat higher for heartwood. However, it is difficult to say, to which extent if any, are these differences caused solely by properties accompanied with heartwood, such as its low moisture content. Also deMontmorency (1964) has made laboratory-scale groundwood, separately from sapwood and heartwood. In his study he used four Canadian softwood wood species, i.e. *Picea mariana, Picea glauca, Picea engelmannii* and *Abies balsamea*, one tree from each species. Supporting the results obtained by Alftan, von (1958), he concluded that sapwood produced generally stronger pulp with higher long fiber content, than did naturally occurring heartwood. However, when the moisture content of sapwood were reduced to that of heartwood, this advantage was partly lost. Thus, the differences in moisture contents of sapwood and heartwood explained most of the superiority of sapwood in grinding. Results from Bengs and Lönnberg (1994), who made laboratory-scale pressure groundwood (PGW) separately from Norway spruce sapwood and heartwood, are well in line with the above findings. However, pressurizing along with elevated temperature did partly offset the effects of dry heartwood.

Table 9. SGW pulps made from Norway spruce sapwood and heartwood (Alftan, von 1958).

	Heartwood SGW	Sapwood SGW
Wood properties		
Basic density, kg/m^3	460	460
Growth ring width, mm	1.80	1.96
Moisture content, %	47	59
Latewood content, %	18.4	28.0
Pulp properties		
Freeness, ml	116	131
Bauer McNett fiber fractions		
R28 mesh, %	13.8	23.0
R48 mesh, %	22.1	19.7
R100 mesh, %	17.0	15.6
R200 mesh, %	13.4	12.4
P200 mesh, %	33.7	29.3
Breaking length, m	3000	3700
Bursting surface, m^2	19.0	20.4
Tearing surface, m^2	0.92	1.03
Specific energy consumption, kWh/t	1120	1265

For refiner-based pulps, and especially TMP, there are not many literature references related to this subject. This emphasizes the fact that the importance of heartwood is not very profound in mechanical pulping systems using wood chips as their raw material. It is intuitively clear that efficient mixing of heartwood and sapwood occurs when wood is chipped and subsequently processed. Moreover, the feasibility to moisten wood in chip form is considerably greater than in the case of pulpwood bolts. However, it should be mentioned, that the heartwood in some wood species prevents the extensive use of these species for mechanical pulping. Some indirect data from thermomechanical pulping Norway spruce heartwood can be obtained from Lindström et al. (1977). In their study of Scots pine TMP, they refined separately also spruce sapwood and standard spruce pulpwood for comparative reasons, the latter assortment having essentially a portion of heartwood in it. Refined to a given level of drainage (CSF), sapwood from spruce consumed about 10 % less refining energy. However, they provided no data on pulp quality obtained from these assortments. Contradicting results to the above has also been found. Namely, in a laboratory-scale study made by Moldenius and Höglund (1987), TMP from Norway spruce sapwood consumed approximately 20 % more refining energy at the same freeness level than that from heartwood. Furthermore, in his study, Braaten et al. (1993) found no significant differences in the specific energy consumption of spruce TMP made from various spruce wood assortments.

According to Höglund and Wilhelmsson (1993), heartwood from Norway spruce give generally TMP which is weaker, but have better optical properties than that made from sapwood. In this case, the obvious cause for differences in both pulp properties is not the existence of heartwood or sapwood, but purely their tracheid morphology, i.e. the high juvenile wood content in heartwood. As in a study by Barbe et al. (1993), who studied the effects of chip moisture content on TMP (see Section 2.3), high heartwood content (low moisture) would presumably produce elevated shives content and poorer strength properties for resulting pulp. Perhaps the most profound effect caused by raw material having a high content of heartwood, is the ununiformity of such wood raw material entering the process. As in the case of wood basic density or wood moisture content (Sectionss 2.2 and 2.3), continuous variation in TMP quality and energy consumption can be attributed largely to heterogenous raw material flow, to which pulping process cannot yet respond.

2.8.3 *Summation*

Heartwood is a wood tissue in conifers where no living cells are found. In Norway spruce, grown in southern Finland, the core of heartwood initiates to form around the pith during the first few decades of tree life. Wood tissue, outside the heartwood zone, and needed for physiological purposes in a tree, is called sapwood. It is not exactly know why heartwood is being developed in most wood species. The average content of heartwood is generally highest in old trees. Spruce pulpwood assortments, like saw mill chips, tree tops and thinnings, used normally for thermomechanical pulping, have typically only a minimum content of heartwood, whereas in older stems, the heartwood percentage is greatest at the base of a stem, being usually over 60 %. In pulpwood from southern Finland, the average content of heartwood varies from about 20 to 40 %.

Heartwood differs from sapwood mainly due to its higher extractives content, considerably lower moisture content, and poor permeability. Since in Norway spruce, the content of extractives is almost equal between those two wood tissues, and generally low in quantity, the only major difference is the moisture content, associated with pit aspiration phenomena. Typically, spruce sapwood have 54–65 % moisture content, whereas that in heartwood is only 25–32 %, determined on wet basis. In groundwood pulping, where roundwood bolts are used, this difference is critical, resulting in generally poor pulp quality. The effects of heartwood on the manufacture of TMP from Norway spruce, are not well estabished yet, but are minor compared to impacts of other factors, such as fiber morphology. When wood with high heartwood content is being refined, elevated shives content and somewhat poorer strength properties could be expected. Negative effects attributed to heartwood in groundwood processes, can be largely offset by the use of wood chips as a raw material in refiner-based processes.

2.9 Knotwood

A *knot* is a *branch* base that is embedded in the wood of a tree trunk, this stemwood part being referred to as *knotwood.* Since branches constitute an essential part of the tree structure and life, it automatically follows that there are always some knots in stems or logs of coniferous trees, and wood with absolutely free-of-knots does not exist, except in small pieces of wood. The number, size and type of knots, and thus amount of knotwood, formed in the wood of a tree depend on the number and size of branches from which they originate, the age which the branches die, and the length of time dead branch stubs remain on the tree. Knots are always associated with the presence of compression wood. Norway spruce, among other spruces, is distinctive of its very slow natural pruning process, the stem being usually covered down to the roots with quantity of dried branches (Wegelius 1939). In terms of mechanical pulping, knotwood, making usually about few percents of the stem volume, is commonly known to have only negative influence due to its properties. Thus, as a major disturbance in wood, its effect must be eliminated or minimized prior to, during, and/or after pulping.

The most extensive study on knotwood properties in softwoods is that of Wegelius (1939), which deals with Norway spruce. The properties of knotwood deviates dramatically from the adjacent normal stemwood in several ways. Firstly, knotwood is much more heavier than stemwood. Typically, basic density values ranging from 700 to 1000 kg/m^3 has been obtained for Norway spruce knotwood, compared to average values of 380–400 for spruce pulpwood (see e.g. Hartig 1896, Klem 1933, Boutelje 1966, Hakkila 1968, Eskilsson 1972, Lehtonen 1980). The reason why knotwood is extremely heavy can be attributed to its high extractives content, fiber morphology, and finally, the associated compression wood content. Partly for the same reasons, knotwood have a low moisture content, this being only 20–30 % in spruce (Boutelje 1966). When tree ages, resinification always occurs in knots causing the extractives content in spruce knotwood to reach well over 10 %, and maximum values of even 30–40 % (Wegelius 1939, Boutelje 1966), whereas normal stemwood has only about 1–2 % extractives (Section 2.10). Irrespective to wood extractives, knotwood deviates chemically from normal wood by consisting about 15 % more lignin and 30 % less cellulose (Hägglund and Larsson 1937).

In terms of fiber morphology, knotwood is a very heterogenous wood tissue consisting of several kinds of wood fibers (see e.g. Hartig 1896, Wegelius 1939, Boutelje 1966). Typically, over half of the tracheids in knotwood are compression wood fibers. Fibers in knotwood are generally short, smaller in diameter, and more variable in cell wall thickness than those in normal wood. Table 10 shows some important properties of Norway spruce knotwood compared to normal stemwood.

Table 10. Some important average wood and fiber properties of knotwood and stemwood in Norway spruce.

Wood property	Knotwood	Stemwood
Basic density, %	800–880	377–450
Fiber length, mm	1.0–1.1	1.9–3.7
Fiber wall thickness, µm	3.0–5.5	4.0–6.0
Fiber diameter, µm	36.0	46.3
Coarseness, mg/m	0.080	0.205
Radial shrinkage, %	3.1–7.8	3.84–6.92
Longitudinal shrinkage, %	0.5–6.1	0.12–0.32
Tangential shrinkage, %	3.7–8.8	6.53–9.30
Moisture content (dry basis), %	23.0–31.0	33 (hw), 146 (sw)
Lignin content, %	33.0	28.6
Extractives content (acetone), %	10.8–13.4	0.5–2.0
Compression wood content	65 %	very small

Sources: Boutelje (1966), Wegelius (1939), Timell (1986), Eskilsson (1972)
(hw) = in heartwood, (sw) = in sapwood

2.9.1 *Occurrence of Knots and Variation in Knotwood Content*

Surprisingly few investigations have been devoted to the amount and distribution of knots in conifers, despite the universal occurrence of knots and their great influence of raw wood quality. There are, though, reports concerning the number, size, and angle of the branches and some related factors causing these. But, perhaps due to laborious methods of analysis, the absolute volume or weight of knots and the changes caused thereby in the structure of wood have on the whole been left for lesser observation (Timell 1986). By far, fortunately the largest number of investigations of the incidence of knots in conifers has been devoted to Norway spruce.

There are some studies, where the volume of knotwood has been reported to be as high as 10–15 % in Norway spruce stems (Gaalaas 1945, Wegelius 1946). These are definitely exceptions from the rule. For instance, Klem (1952) found 0.18–1.05 % of knotwood, by volume, in a stand of Norway spruce in 1940, values which have been reduced to 0.16–0.44 % a dozen of years later as the stand had become closed. Other investigators have reported values ranging from 0.5 to 4.5 % for the volume-based knotwood contents in spruce stems (see e.g. Nylinder 1959, Hakkila and Rikkonen 1970, Lehtonen 1980, Okstad 1988). However, in spruce pulpwood logs arriving the mill, average content of knotwood has varied from 0.62 to 2.3 % (Hakkila and Rikkonen 1970, Okstad 1988).

As already pointed out, the weight percentage of knotwood is much higher than the volume percentage, which definitely makes this kind of woody tissue more interesting in wood for pulping. For instance Lehtonen (1980) reported that the knotwood volume in Finland grown spruce trees were 0.5–2.0 %, corresponding to a weight range of 1.1–6.7 %. However, Nylinder and Hägglund (1954) reported much lower average knotwood weight percentages, being 0.10–2.3 %, in their massive study of Sweden-grown spruce. It can be stated from the foregoing that considerable variation exists in average knotwood content and its determination is not simple. Perhaps more important than knowing simply the average knotwood content, might be the fact how knotwood content varies in a stem and in what kind of trees and stems the knotwood content is extremely high on an average. The following figure (Fig. 34) presents the volume of knotwood related with the stem height in Norway spruce and Scots pine.

It is quite obvious from the above that in merchantable parts of the spruce stem, toplogs contain more knotwood than butt logs. The fact that the ratio of knot volume to stem volume increases toward the top of the tree is only what can be expected, since the branches gradually cease to grow radially, beginning at the lower part of the crown, while the stem continues to increase its girth. There is a quite good agreement that fewer knots (less knotwood) are present in trees grown in dense stands than in more open stands (see e.g. Wegelius 1939, Klem 1952, Nylinder 1959). Trees in open stands always have coarser branches and accordingly larger knots, than those in dense stands. It has also been shown that the proportion

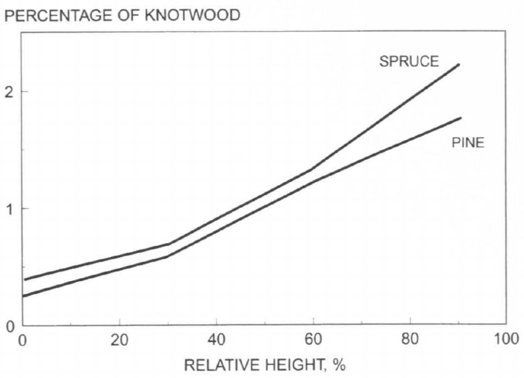


Figure 34. Variation of volume percentage of knotwood with stem height in spruce (*Picea abies*) and pine (*Pinus sylvestris*) (Nylinder 1959).

of knotwood tend to decrease with decreasing with of annual increment and with increasing age of the tree (Nylinder and Hägglund 1954, Hakkila 1989). Thus, the greatest amount of knotwood is found in relatively young, vigorous spruce stems grown in open spacing, whereas the smallest content is found in old, slowly-grown supressed trees.

2.9.2 *Influence of Knotwood on TMP Manufacture*

In chemical pulping of wood, irrespective to its high density, knotwood is known to lower the yield and quality of pulp. When wood with high knotwood content is pulped, the consumption of effective cooking chemicals increase, yet knots will defiberize only partially (see e.g. Wegelius 1939, Nylinder and Hägglund 1954, Nylinder 1973, Law and Koran 1982). However, in chemical pulping industry, it is possible to some extent to exclude knot wood by separation (Boutelje 1966). Studies on the effect of knotwood on mechanical pulping and pulps are much more fewer.

It has been commonly known that in *wood grinding*, the hard, dense, and brittle compression wood in the knots turns into a dark powder. The high resin content impairs the grinding efficiency and lowers the quality of the pulp. Energy losses are found to occur because of the different orientation of the fibers in knot and in stem (Brax 1936). Since no studies have been made where Norway spruce knotwood vs. normal wood were refined thermomechanically, except that of Brill's (1985), and Sahlberg's (1993) laboratory scale refining, it is expected that the knotwood's behavior is, at least to some extent, similar than in wood grinding.

Firstly, in preparation of wood for pulping, the hard knot wood is said to dull the chipping knife, leading to compression failures in wood. Secondly, the knots and the abnormal wood around them, produce poor and uneven chip configuration although some of the knotwood, i.e. whole knots, can be rejected as overthick or overlong particles from the retained accept material in chip screening (see e.g. Hartler 1977, Parham 1983, Hoekstra et al. 1983). When TMP is considered, knotwood itself, due to its abnormality, could be expected to behave differently from normal wood in refiner, and also produce pulp of low quality, because of numerous reasons, discussed here. For instance, a low initial moisture content of knotwood can also attribute to poorer quality and higher energy consumption of the resulting pulp (Virkola et al. 1986). The properties of knotwood and its fibers were compared earlier, in Table 10. Short, thick-walled and chunky-shaped knotwood fibers attributes to pulp and paper of low strength properties (Wegelius 1946, Parham 1983a). Obviously, the bonding potential of such TMP fibers is relatively low. Both the intrinsic strength and, somewhat surprisingly, stiffness of the knotwood fibers has been observed to be low, even if corrected for the small dimensions (Eskilsson 1972).

Brill (1985) tried to find out the effect of knotwood using Norway spruce branches instead of knots, in the manufacture of TMP. In his trials, 0 %, 1–10 % and 100 % branchwood contents were used in the mixtures of branchwood /stemwood. It should be noted here that the properties of branches are not the same, but quite close to those of knotwood, thus, making this comparison justified (Wegelius 1939, Eskilsson 1972). Some results are shown in Table 11 and Figure 35.

According to Brill's (1985) results, knotwood will produce significantly weaker pulp than stem wood, with generally higher power consumption. Despite the same light scattering value, knotwood results almost 10 units lower ISO-brightness. This is a direct consequence of its high lignin content, and thus, high light absorption coefficent. Finally, he concluded from this study that small portions, when well below 10 %, of knotwood do not significantly lower the resulting TMP quality. On the contrary, when Sahlberg (1993) recently studied the influence of spruce knot fibers on the properties of TMP, she found that even 2.6 % knot content in chips (by weight) yielded pulp with lower strength, higher bulk and poorer surface strength, than handsheets made from knot-free pulps. According to her results, this inferior pulp quality can be attributed to differences in fiber characteristics and also to the low moisture content in the knots, the both subjects discussed earlier in this section.

Table 11. TMP properties, refined from Norway spruce branchwood and stemwood (Brill 1985).

TMP property	Stemwood	Branchwood
CSF-freeness, ml	100	100
Specific energy consumption, kWh/t b.d.	1900	2040
Tensile index, Nm/g	40	14
Tear index, mNm^2/g	7.2	2.5
Sheet apparent density, kg/m^3	440	350
ISO Brightness, %	64	55
Light scattering coefficent, m^2/g	64	64

Knotwood yield fibers and pulps that are considerably darker than made from normal spruce stemwood, as proved also by Brill (1985). In addition to the high lignin content in knotwood, the poor optical characteristics can also be subjected to relatively thick-walled fibers in knotwood. Knots in conifers are associated with compression wood in two different ways. A large proportion of every knot consists of compression wood. Furthermore, compression wood frequently also occurs within the stem wood surrounding the knot (Wegelius 1939). According to Ilvessalo-Pfäffli and Laamanen (1976), the dark bundles of compression wood fibers often present in softwood pulps, can originate from either stem compression wood or, especially from knot wood.

The knot particles are also difficult to bleach in TMP (Annergren and Hägglund 1979, Brill 1985). In their study of peroxide bleachability of Norway spruce TMP, Annergren and Hägglund (1979) found that knotwood particles accounted about 10 % of all visible impurities (shives and dirt specks) in bleached TMP, the rest originating from bark, extractives and fiber bundles. More on the impairing effect of high extractives content in wood can be found in Chapter 2.10 of this study. Not only is knotwood itself undesirable but often there are resin deposits and ingrown bark associated with the knots, making the resulting TMP of very poor quality (Parham 1983). As being obvious from the foregoing, the negative impact of knotwood is often greater than its amount in pulpwood could suggest.

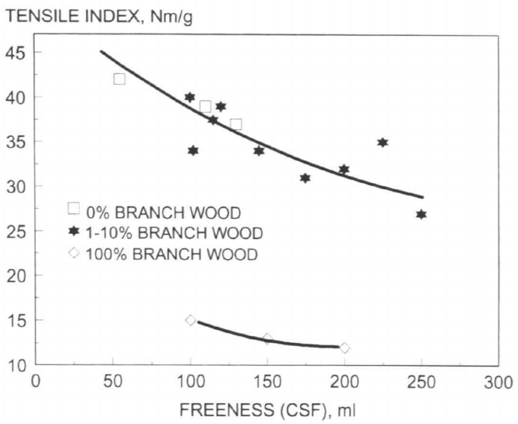


Figure 35. Tensile index vs. CSF for TMP from 100 % stem wood, 100 % branch wood and 1–10 % branch wood mixed in stem wood and stemwood (Brill 1985).

2.9.3 *Summation*

Since branches constitute an essential part of tree structure and life, it automatically follows that there are always some knots in stems or bolts of coniferous trees. The average amount of knotwood in Norway spruce pulpwood varies from 0.5 to 2.0 %. Although in many studies, top logs and of mature spruce stems and young trees are found to consist of slightly more knotwood, about 2 %, whereas butt logs have the smallest content, about 1 % or less of volume, there is much contradicting data, indicating that no distinctive correlations have been established with stem part or any outward sign, such as stem size, branch size, tree social status, or type of pulpwood assortment.

Occasionally, for instance in case of wood shortage, some mills have to accept logs from stands consisting of wood with high knots content, being even more than 10 %. In the light of this, knotwood can form a major problem in thermomechanical pulping. Knotwood deviates from normal stemwood by having extremely high density, solids content, extractives content, lignin content, compression wood content and shrinkage, whereas the fiber dimensions and properties are generally inferior. For these reasons, knotwood produces poor thermomechanical pulp obtained with elevated energy consumption. Generally, all strength and optical properties are weaker compared to normal stemwood pulp. More often, the actual knotwood content in spruce pulpwood is found to be even lower than above, being only 0.5–1.0 %, and after chipping, screening and wasting, it becomes even lower in the chip flow prior to thermomechanical pulping. Therefore, the total effect of knotwood on the manufacture and quality of pulp, is only marginal.

2.10 Wood Extractives

All the constituents in wood, other than cellulose, hemicelluloses and lignin, are generally called *extractives*, since they can be extracted with organic solvents such as acetone or dichlorometane (Pensar 1977, Fengel and Wegener 1989). To avoid confusion, technical terms *resin* or "*pitch*", as the non-polar extractives are sometimes called in pulp and paper making, should not be used as an overall expression of extractives, since they can in many cases refer to chemical constituents which do not originate from wood at al. Extractives are formed through a variety of biosynthetic pathways, however, knowledge of their formation and functions in a tree is still unsufficient. Their role as a major disturbancy in pulping and paper making is commonly recognized.

Wood extractives is not a uniform concept and they can be classified in several ways. They are often subdivided by their function in a tree (Assarsson and Åkerlund 1966, Sjöström 1981). *Pathological extractives*, located in resin canals, are mainly composed of resin acids and monoterpenes, protect the wood against biological degradation. *Physiological extractives*, located in the ray parenchyma cells, are rich in fats and constitutes a supply of reserve food. Pulp and paper mill personnel are usually interested categorizing the extractives into chemical classes, which have a direct bearing on the pulping process or paper machine operation, namely, *saponifiables* and *unsaponifiables* (Sithole 1992). By their chemical characteristics, and irrespective to the solvent, which the extraction is performed with, nonvolatile wood extractives are most often identified as *lipophilic* and *hydrophilic extractives* (Assarsson and Åkerlund 1966, Pensar 1977, Ekman 1979a, 1979b, Holmbom 1993).

When wood as a raw material for pulp and paper products is concerned, the lipophilic compounds form the most important group of extractives in fresh stemwood. They are non-polar compounds, being composed of free and esterified fatty acids, resin acids, free and esterified sterols, diterpene and triterpene alcohols, which together comprise over 90 % of the spruce wood total petrol ether-soluble extractives detectable by gas chromatography (Ekman 1979a, 1979b). Hydrophilic extractives, being soluble to polar solvents, are comprised mainly of phenolic compounds like tannins, lignans, flavonoids, stilbenes. Moreover, a small part of extractives are composed of certain sugars and inorganic salts, which all are soluble to water. When wood is extracted, especially with acetone or hot water, also some other water-soluble hydrocarbon components are derived from wood, as a small part of polysaccharides are always solved or hydrolyzed from the cell wall structure (see e.g. Assarsson and Åkerlund 1966, Back 1969, Pensar 1977).

2.10.1 Location and Content of Extractives in Wood

The location and nature of wood extractives highly affects the accessibility of these substances in pulping operation, as shown later. A major part of extractives are located either in resin canals, both vertical and horizontal, or in parenchymatous ephitelial cells. In fact, this cell type comprises almost 5 % of the total cell volume in spruce, the major part being longitudinal fibers (Trendelenburg and Mayer-Wegelin 1955). Resin canals are always surrounded by these ephitelial parenchyma cells, however, most these cells being located in wood rays (Ollinmaa 1959). Table 12 gives some comparative data on extractive content, parenchyma cells and ray tracheids of Norway spruce and Scots pine.

Table 12. Comparative data on spruce (*Picea abies*) and pine (*Pinus sylvestris*) extractives content and distribution of extractives in wood and pulp (Sjöström 1981).

Data	Spruce	Pine
Nonvolatile extractives (% of dry wood)	0.8	2.2
Distributed (in wood) on		
parenchyma cells (%)	55	30
resin canals (%)	45	70
Ray cells in unbleached chemical pulp (weight %)	6	8
Distributed (in pulp) on		
parenchyma cells (%)	85	30
ray tracheids (%)	15	70
Mean frequency of parenchymatous to tracheidal ray cells (in pulp)	2.7 : 1	1 : 2.8
Mean relative pit area of ray parenchyma cells (% of total cell area)	5	50
Mean pit size at radial walls of parenchyma cells (µm)	2–3	12 × 31

In Scandinavian spruce (*Picea abies*) stemwood acetone-extractives content varies from 0.9 to 2.4 % of dry weight, and in pine (*Pinus sylvestris*) from 3.1 up to 6.0 %, which is remarkably more. Highest values are always found in the northern latitudes (Nylinder and Hägglund 1954, Hakkila 1968). Lower values are usually obtained, if for instance dichlorometane or ethyl ether is used as a solvent. Unlike in many conifers, and especially in pines (*Pinus* spp.), the average content of extractives in stemwood is more or less the same in Norway spruce sapwood and heartwood. There are though some studies concluding, that the heartwood extractives content could be 10 % or less smaller than in sapwood (see e.g. Kimlamd and Norin 1972, Pensar 1977, Ekman 1979a, Holmbom 1993). It should be noted that in Scots pine and most pines, the average extractives content in the base of old stems can be normally as high as 10–20 % (see e.g. Trendelenburg and Mayer-Wegelin 1955, Haygreen and Bowyer 1989. Moreover, Ekman (1979a) has studied the composition of Norway spruce extractives and he found that the lipophilic petrol ether soluble extractives from fresh sapwood and heartwood were qualitatively identical, but the amount was higher in the former principally due to differences in fatty acid content. Among the more polar extractives insoluble to petroleum ether, the storage carbohydrates: fructose, glucose and sucrose were typical sapwood constituents and lignans were the major heartwood extractives detectable by gas chromatography.

The top section of Norway spruce shows to have on an average 20 % greater extract quantity than the ground level of a tree, as is also the case with relatively young stems, according to Nylinder and Hägglund (1954). Variation in extractives content between stems growing in the same stand, can result from both environmental or genetical factors. For instance, fast-growing trees have somewhat lower amount of extractives, than slowly-growing trees (Pensar 1977). However, contradicting the above statement trees with high latewood percentage are found to have slightly smaller content of extractives, than trees with low latewood content (Jalava 1952). As already mentioned earlier (Section 2.9.1), the extractives content in knotwood is always higher than that of knot-free stemwood. There is a great variation in different parts of the tree, in the content and composition of extractives during a growing season, a subject that has not been largely studied yet. After felling a tree and during seasoning of wood bolts or chips, the content of extractives is always somewhat reduced and their composition changed (see e.g. Back 1969, Nugent et al. 1977, Pensar 1977, Kukkonen and Niiranen 1983). However, in TMP process only fresh, unstored wood is generally used as a raw material.

2.10.2 Influence of Extractives on TMP Manufacture

In kraft pulping process, wood extractives are known to form an important part in the byproduct yield. On the other hand, sulphite process is known to be generally very sensitive to wood extractives, allowing only wood with minimum content of extractives to be processed (Hillis 1962, Pensar 1977, Sjöström 1981). In TMP manufacture or any mechanical pulp, practically no positive effect or value in any meaning can be attributed to extractives in wood. In fact, some end-products, namely fluff, tissue and food carton pulps require the lowest possible extractives content. Wood extractives, namely fatty acids and lipids, do have a tendency to create unwanted taste and odor in such end-products as foodboards (Holmbom 1993). Moreover, it is known that some softwoods, for instance, douglas fir, jack pine, larches, and some cedars, contain so high quantities of colored extractives in their heartwood that mechanical pulping of this wood tissue is practically impossible due to arising processing problems and end-product defects, among them losses in pulp strength and optical properties (see e.g. Tay and Manchaster 1982, Parham 1983, Malinen 1986, Leask 1987b). Although none of the parts of native Norway spruce does contain noteworthy amounts of coloring phenolic extractives, the same compounds mentioned above, have also found to increase the photo-yellowing of mechanical pulp (Forsskåhl and Jansson 1990). Toxicity of effluents from both TMP mill and bleaching plant is known to increase with the increasing amount of extractives, and especially resin acids. In a paper manufacturing process extractives cause foaming problems and "pitch" contamination in process equipment and paper end-product (Hillis 1962).

Physical accessibility of extractives located in resin canals is fairly high, especially in kraft pulping (Sjöström 1981). This is true also for mechanical pulps, but when wood is pulped mechanically without chemicals, majority of the extractives in the wood fed to the process, remain in pulp (Back 1969, McMillin 1969, Allen 1975, Kappel et al. 1991). In bleached softwood kraft pulps, the extractives percentage is very close to zero. Being so, the net importeur of wood extractives constituents in the manufacture of wood containing papers is definitely the mechanical pulp component. Only a small portion of these compounds are being volatilized or dispersed and then washed-out during the pulping process.

According to Hartler (1985), there are strong indications, that the extractive components will be mechanically dispersed during TMP-refining. A small portion of them will stay in dispersion and be washed out, whereas others will either never come out from the solid phase or will agglomerate quickly and precipitate on the fibers. In thermomechanical pulping process, only a minor part of extractives dissolve during refining, the main part being dissolved in conjunction with pulp post-treatment, after hot disintegration, according to Järvinen et al. (1979). In unbleached spruce-TMP pulps the extractives content, extracted with dichlorometane, ranges from 0.6 to 1.1 % and after peroxide bleaching from 0.3 to 0.4 %. The corresponding values for CTMP are 0.2...0.3 % in unbleached and 0.1...0.2 % in bleached pulp (Kappel et al. 1991, Holmbom 1993). Ditionite-bleaching is more selective and does not significantly reduce the extractives content in mechanical or chemimechanical pulping .

Extractives enriched *parenchymatous cells* are commonly found in finer fractions of TMP and in pulp rejects (Hooper 1987, Heikkurinen 1992). In Norway spruce parenchymatous cells, the pore area (pits) is only 5 % of the total wall area and these cells are also found to be relatively durable against mechanical forces (Back 1969). Poor extractives accessibility in pulping and papermaking operations, i.e. "picth problems" can usually be attributed to these longitudinal and ray epithelial cells (Sjöström 1981). In addition to the above, it is also assumed by Wood and Karnis (1977) that the tendency to cause linting in TMP containing newsprint can be partly attributed to both parenchymatous and ray cells. They are of short length, less than 1 mm, and have a very low specific surface to form fiber-to-fiber bonds.

In pulp and papermaking, the dilemma of wood extractives seems to be: the more extractives has been removed during the wood storage and pulp manufacture, the less they are of papermaker's harm and vice versa. In paper machine circulation waters, the extractives components tend to form small particles, 100 nm to 1 µm of size. These *micelles* are in liquid-crystalline phase and both lipophilic and hydrophilic constituents are found in a same particle. Also somewhat surprising is the fact, that extractives components originating from totally different wood tissue i.e. resin canals and parenchyma cells, can be found agglomerated together (Holmbom 1993). These agglomerates form harmfull contaminant both on process equipment and paper end-product. In their study of dirt contaminants in TMP made from Norway spruce, Annergren and Hägglund (1979) found that both in unbleached and bleached pulps, extractives (or "pitch") components accounted more than 10 % of visible dirt specks, the major influence coming from bark components. It was also shown in SEM micrographs, that many dirt specks consisting of fiber clusters or shives, were harmfully covered with "pitch". Moreover, large agglomerates of extractives can cause holes in paper, and a web break in the coating unit, paper printing apparatus or dirt defects in uncoated papers (see e.g. Allen 1975, Annergren and Hägglund 1979, Simard et al. 1988).

Also paper strength properties of mechanical pulp containing papers, irrespective to those above mentioned "pitch" spots in paper web, is found to be affected by extractives, when in large quantities. Especially for groundwood pulps, the presence of "pitch" is claimed to be detrimental to paper strength by preventing interfiber bonding and by blocking active sites on the fiber surfaces and by lubricating effect (see e.g. Brandal and Lindheim 1966, McMillin 1969b, Nyblom 1979, Tay and Manchaster 1982, Holmbom 1993). A study made by Brandal and Lindheim (1966), it was found that groundwood pulps produced from Scots pine, contained certain components in the residual pitch which inhibited bonding extremely effectively. Namely, they found 57 % increase in tensile strength and 35 % increase in tear strength, when pulps were extracted with acetone. Moderate effects were also obtained for Norway spruce groundwood, in which the corresponding increases were 16 and 10 %. The amount of material removed from pulps by extraction was about 3.5 % for pine and 1.7 % for spruce. They found that pulp brightness was not affected by extractives.

Results that are in line with the above have been obtained by Tay and Manchaster (1982) for Canadian wood species, e.g. jack pine (*Pinus banksiana*) wood, which typically have about six times more extractives than the Norway spruce. However, as concluded by them, extractives were by no means the predominant factor causing poor interfiber bonding in refiner mechanical pulps made from jack pine, but the main reason being the coarse and stiff fibers of pine. In a study made at FPPRI (Nyblom 1979), it was found, that TMP made from Finnish pine (*Pinus sylvestris*), gained 20 % and 26 % increase in tensile and tear index, when extracted wood chips were used in the manufacture. This positive effect on pulp strength properties was even greater, when the whole pulp was extracted. While spruces originally do have a low content of extractives, their impact in TMP manufacture must be of the same kind, but much more moderate, as shown above for groundwood pulps. It should also be noted that accessibility of wood extractives must be much more better in TMP process, with high temperature and pressure, and using chips as a raw material, than in groundwood process.

Although being not a factor in terms of TMP quality, it should be borne in mind that wood extractives, either in the form dissolved material from wood extractives during the pulping process, later from the paper machine, or bleaching plant, are evident sources of mill effluents, influencing especially on their toxicity (see e.g. Back 1973, Järvinen et al. 1979, Holmbom 1993, Jørgensen et al. 1994, Hoel and Aarsand 1994). According to studies by Jørgensen et al. (1994), and Hoel and Aarsand (1994) of TMP effluents, it is mainly the resin acid components in Norway spruce extractives that cause toxicity, whereas the acute toxicity of phenolic components, such as lignans were relatively low, being also biodegradable in nature. Therefore, it can be concluded that the total extractives content of wood used as raw material have a direct bearing on effluent toxidity.

2.10.3 Summation

Softwood extractives, an essential part of tree growth processes, are consisted of a great number of compounds of which chemistry is quite complex, as a whole. They are usually divided into lipophilic and hydrophilic components, in terms of their technical nature. The origin and largely the location of extractives in a stem, is the parenchymatous cells, as well as resin canals, the latter having quite good accessibility in pulping processes. Unlike in most conifers, in Norway spruce there is no extensive deposition of extractives into tracheids during the heartwood formation, but the average total amount of extractives is more or less same in both heartwood and sapwood. Moreover, despite that variation occurs in the average content of extractives, within and between the *Picea abies* stems, this variation is negligible compared to that between wood species. In southern Finland the average (acetone) extractives content in spruce pulpwood varies approximately between 1–2 % of o.d. wood weight, being a very low value if compared to pine (*Pinus sylvestris*), for instance, which typically have several times more extractives, limiting its use for TMP a sole chip furnish.

In TMP pulps made from sprucewood, the average extractives content is usually well below 1 %, which amount does not affect pulp strength or optical properties in practice. Perhaps the disturbancies that have the most negative effects on pulp and paper manufacture is the deposition of extractives components into processing equipment, paper end-products, as well as mill effluents, these effects being mostly hard to quantify. They are always present due to accumulation phenonmenon. However, the total content of extractives arriving along with wood raw material tend to have a direct effect on the above.

2.11 Conclusions from the Theoretical Study

2.11.1 Important Wood and Fiber Properties of Norway Spruce as a Raw-Material for TMP

Basing on the what was discussed earlier in the theoretical study, the following matrix (Table 13) is made in purpose to summarize the wood and fiber properties of Norway spruce wood, which were found to have influence on the manufacture of thermomechanical pulp (TMP) in terms of either pulp yield, pulp quality, specific energy consumption or other manufacturing cost, paper end-product properties or its market value. Listing is not definitive and does not show their relative importance, which can be more or less a subjective and complicated matter. However, when normal Norway spruce wood is concerned, the fiber morphology and juvenile wood content are considered to give the most pronounced effect on TMP, whereas those properties coming last in the list, such as basic density or knotwood content, have less importance.

Despite the pronounced impact of fiber dimensions and juvenile wood content, all of the above wood property impacts on TMP can have a direct bearing either on the pulp and paper manufacturing process, or pulp's serviceability in its end-use, that is, various paper products. Pulp specific energy consumption and yield affect directly the production economy. Moreover, TMP strength properties and shives content affect mainly the runnability of paper, both in paper machine and printing room. Optical properties affect mainly paper printability and how it fits for use in various applications. Pulp sheet structure is a result of pulp particle properties and can largely affect paper printability. Shives and agglomerates of which origin is either bark, knots or extractives, can cause dirt specks in paper being unattractive for an end-user. "Pitch" deposition on pulp and paper making equipment, caused by wood extractives, generally decrease the quality of production.

As being obvious from the theoretical investigation, the properties of wood affect thermomechanical pulping in two principal ways. Firstly, continuous variations in wood basic density and moisture content occurring naturally in the chip flow tend to cause accordingly variation in refining consistency, which, in turn, affects pulp uniformity and energy consumption. The above negative effects are especially harmful, since they cannot be efficiently offset by any process control variable, such as production rate. However, it seems that these impacts can be increasingly minimized with installation of novel process control systems and segregating wood raw material into more uniform quality groups. Secondly, the obtainable properties of pulp and derived paper end-product largely depend on the kind of wood used. In this respect, the greatest influence can be attributed to differences between various wood species. To date, however, it has become clear that the properties of mechanical pulp obtained from various wood assortments from the same species largely differ. Despite the above, most mechanical pulp mills do not have a strategy to segregate their wood raw material from the same wood species, which would facilitate the separate pulping of a specific fiber source.

The need for more work on the relationship, if there is one, between wood characteristics and the resultant mechanical pulp properties has been frequently recognized by many investigators (see e.g. Leask 1981, Corson 1993, Karnis 1994). Attempts to relate wood properties to mechanical pulping and related end-products has been made ever since the pulping industry was established.

Table 13. Matrix of important wood characteristics of Norway spruce and their expected general impacts in TMP manufacture, as derived from the theoretical investigation. The wood properties and their presumed effects on TMP are not in any definitive order

Wood property	Average values in stems	Major pattern of variation; influenced by	General importance for TMP	Area of expected primary impacts on TMP	Influence on TMP	Area of expected secondary impacts on TMP	Influence on TMP
Tracheid length	1.5–3.5 mm	within-tree (radial, axial); wood age	major	strength properties fiber composition	high average fiber length equals good pulp tear strength and long fiber content	strength properties sheet structure	high average fiber length equals high tensile strength, but poor sheet formation
Cell wall thickness	2.0–5.0 µm	within-tree (radial, axial), wood age	major	sheet structure fiber composition	thick-walled fibers equal poor sheet structure in terms of surface roughness, fiber rising and other disturbances, but elevated long fiber content	optical properties	high average cell wall thickness equals poor light scattering power
Tracheid diameter	20–35 µm	within-tree (radial, axial); wood age	major	sheet structure	large diameter fibers (uncollapsed) cause disturbances in sheet structure, such as roughness, fiber rising	strength properties optical properties	large diameter fibers, but with thin walls equal good tensile strength and light scattering power
Juvenile wood content	10–100 %	within-tree (radial, axial); wood age	major	optical properties strength properties sheet structure	high juvenile wood content equals elevated shives content scattering power, brightness, printing properties, but poor tear strength	strength properties	high juvenile wood content equals poor binding
Moisture content	40–60 %	within-tree (radial, axial); wood age	intermediate/ minor	shives content energy consumption[1] strength properties[1]	low moisture content equals elevated shives content large variations in moisture content cause pulp ununiformity and elevated energy consumption	strength properties energy consumption	with extremely low chip moisture content, all major strength properties are negatively affected. Also elevated energy consumption is expected
Heartwood content	0–60 %	within-tree (radial, axial); wood age	intermediate/ minor	shives content	high heartwood content equals elevated shives content	energy consumption strength properties	with extremely high heartwood content, increases in pulp energy consumption and decreases in strength properties are expected
Latewood content	15–30 %	between-trees; growth rate within-trees (radial); wood age	minor	sheet structure	high latewood content equals surface disturbances, and poor sheet structure	fiber composition	high content of latewood in chips would presumably produce more long fibers to pulp
Extractives content	0.8–2.3 %	between-trees, physiological reasons	minor	deposition on processing equipment dirt specks	high extractives content equals "pitch" problems in processing equipment and dirt specks in pulp	effluent toxicity	high content of extractives remained equals elevated effluent toxicity
Knotwood content	0.5–2.0 %	between-trees; growth conditions within-tree (axial); relative height	minor	shives content dirt specks	high knotwood content equals elevated amount of shives and dirt specs	energy consumption strength properties optical properties	extremely high knotwood content equals elevated energy consumption, poorer strength properties and lower brightness
Basic density	300–500 kg/m^3	between-trees; growth rate between-stands; growth rate	minor	energy consumption[2] strength properties[2]	constant variations in basic density cause uniformity in pulp quality, especially in pulp strength and elevated energy consumption	pulp yield	low wood basic density equals low volume-based pulp yield

[1] = pulp unevenness caused by fluctuations in chip moisture, [2] = pulp unevenness caused by fluctuations in chip basic density. These effects are caused by normal wood variation and cannot be largely controlled by process variables.

However, for instance McMillin in his comprehensive studies (1968a, 1968b, 1969), found no significant correlations between gross wood characteristics, such as basic density, latewood content, or growth rate, and mechanical pulp properties, such as refining energy or sheet strength. Fiber morphology explained part of the variation in pulp properties, though, but these properties were dependent rather on the applied refining energy or other independent variables, such as sheet density. Despite the fact that relatively great magnitude of knowledge of relationship between wood and pulp behavior has been obtained to date, the mechanical pulping industry has not yet developed a comprehensive model (Corson 1993).

It is intuitively clear that making such model would be without practical justification due to the nature of mechanical pulp and its particles, different pulping mechanisms involved (e.g. SGW, PGW, TMP), and finally, the great heterogeneity of wood as a raw material. Namely, the reason why most studies fail when trying to relate some single wood property, such as basic density or fiber diameter, to some mechanical pulp property is at least twofold. The main limitation giving the definite impact of a change in some single wood property on some single TMP property, is the fact that many wood properties tend to be more or less interrelated, which applies also to many pulp properties. If correlations are found, they tend to be applicable with only limited wood species, wood type, range of properties, or extent of pulping conditions. For instance, latewood fibers in juvenile wood differ dramatically in size from those found in mature wood. More importantly, mechanical pulps are not only a function of its fibers, but these properties are largely determined by the characteristics of its smaller particles, being quite a complex function.

Therefore, more practical approach is needed. Instead of attributing quality impacts to single wood properties, Corson (see e.g. 1983, 1991, 1993), in his extensive pilot-scale mechanical pulping studies of radiata pine (*Pinus radiata*), has concluded that good correlations exist between the type of wood and pulp properties. The main factor causing variation in the intrinsic wood properties in a coniferous stem is the age of the growth increment calculated from the pith. The above approach will be also used in the empirical part of this investigation, where most of the discussion so far will be operationalized in terms of mill-scale TMP manufacture from various Norway spruce wood assortments. In fact, mill-scale studies with such scientific interest have not been made on the subject and only little attention has been given to Norway spruce in this respect. Hypothetical effects of various wood assortments on some quality factors of newsgrade TMP will be given in later section prior to the empirical study (see Section 2.11.3).

2.11.2 Selection of Spruce Pulpwood Assortments According to Their Pulping Potential

As being clear from the foregoing the most pronounced effects on TMP manufacture are caused by fiber length, fiber cross-sectional dimensions, and juvenile wood content, the last factor being partially interrelated to the fiber dimensions. Moreover, wood moisture content might be of importance, if wood with high heartwood content is used. Effects caused by other factors are either lesser in importance, are not related in any particular wood type, or their effects on TMP cannot be predicted. In fact, calculating an effect caused by a single wood quality factor, such as fiber length, is misleading since it cannot be controlled separately in practice. Instead, wood is being procured to a mill with means of various wood assortments, and the effect of wood and fiber properties must fit to a feasible assortment. In other words, the wood and fiber properties of various assortments may differ significantly in terms of their pulping potential.

Traditionally in Finland, spruce butt log and middle logs, of specified size and quality, of a large stem are graded exclusively as saw logs, thus, not ending up to pulpwood assortments. However, sawmill residual chips from slabs and edgings, i.e. fresh outer sapwood from large logs, is one of the most important pulpwood assortment for pulpmills, and also for TMP mills. The rest of Finnish spruce pulpwood consists of top logs, thinnings wood, disqualified sawlogs. As mentioned in the introductionary section (Section 1.1), occasionally clear-cut spruce stands from regeneration cuttings that were originally aimed for sawmilling, end up to pulp mills, depending on market situation etc. Most often, with the exception of requirement for wood freshness and minimum top diameter, there are neither tight quality requirements for pulpwood, nor are various assortments being utilised to date according to their pulping potential.

As a conclusion of theoretical study, specified assortments are being formed as follows. It is true that relevant pulpwood assortments could be formed in several ways. At least in theory, the following origins of wood and methods of sorting could be basically used:

- Whole-tree chips made from various types of stands
- Sawmill chips and other residual wood, such as sawdust
- Whole-stems from stands of different age-class, i.e. short-rotation wood, first-thinnings, later thinnings, mature stands, and over-mature stands
- Logs from various parts of large stems, i.e. butt log, middle logs and topwood
- Wood from even-aged stands with different site fertilities, i.e. OMT, MT, VT, etc. soil types
- Wood from even-aged managed stands (fast-grown) or natural stands (slowly-grown)
- Selected stems, but only with specific characteristics, from a particular locality, i.e. supressed trees, dominating trees etc.

The above listing covers almost all possible choises if wood with specific pulping properties is to be selected for thermomechanical pulping operation. However, irrespective to the pulping potential of a specified assortment, all of the following requirements must be fulfilled:

1. Desired pulping potential (suitable wood and fiber characteristics)
2. Feasibility in terms of wood harvesting and/or procurement
3. Economical justification of operations involved
4. Sufficiency of wood from each assortment to ensure long term operations in thermomechanical pulp manufacture

Therefore, there are quite few true possibilities available despite the number of choices. Namely, whole tree chips do not fit to the quality requirements of TMP. With the exception of sawmill chips, this is also the case with the residual wood from wood converting industries. Division of logs along stem height do bring out considerably various assortments in terms of thermomechanical pulping. Especially, taking wood from butt logs would be a good base for segregation. However, a sawmill has probably more wood paying ability to buy these logs than for instance an average newsprint mill, and thus, these logs will be mainly forwarded to the sawmilling industry. The extent of environmental wood variation, in terms of site fertility or silvicultural practice, is not so dramatical to justify its use as a criteria of wood segregation, or its effects on the key wood quality factors are only rarely known as a whole. Finally, although there were identifiable characteristics for trees from the given locality which would posses desired pulping characteristics, such operation is not economically feasible yet. It is therefore clear that the assortments to fulfill all the above four points will be mostly those assortments which are being presently used.

Basing on the findings in theoretical study and what has been discussed above, the following spruce pulpwood assortments, of which pulping potential is assumed to vary significantly, are being suggested:

- Sawmill chips
- Wood from regeneration cuttings
- First-thinnings wood

The above wood raw-materials were selected, because they would represent the largest obtainable variation occurring in the major wood properties, in southern Finland-grown Norway spruce, in terms of TMP manufacture (see Table 14). Especially, it is the first thinnings and sawmill chips wood which would represent the two extremes with respect to both fiber dimensions and the amount of juvenile wood, and their expected influence on TMP. Moreover, these assortments would presumably possess a wide range of variation also in minor wood properties, such as latewood content or basic density. Therefore, it is believed, that the above mentioned deviation in wood properties between these assortments would assure enough differences in the obtainable pulp properties. Of special interest in this investigation is finding out the commercial opportunities of first-thinnings wood, since it is never, or only rarely, being pulped as a single raw material component. It should be borne in mind that suitability of a mechanical pulp, and thus, the choice of its wood raw material must always be evaluated based on its use as a furnish component for a given paper end product, which is sold in a specific market. However, this is out of the scope of this study.

Since many of the important wood and fiber characteristics are correlated with wood age, the presence of an old-growth stand from regeneration cuttings in the above listing was seen very important. It is expected that this assortment offers a wide range of fiber characteristics, of which combined effects are not really known yet. Moreover, if the low wood moisture content, usually associated with high proportion of heartwood, has a true negative impact on TMP, these effects would become rationalized via this assortment. It is true that normally the largest part of the old-growth stem is directed for the sawmilling industry as sawlogs, and not chipped as pulpwood. Nevertheless, the tree tops, small-sized logs and logs which do not fulfill the requirement of sawlogs, always end up to a pulp mill. Furthermore, as already mentioned in the background section (Section 1.1) there is a great magnitude of such spruce stands in Finland, being currently under-utilized. Since in some market situations pulp mills do buy logs that traditionally belong to sawlog category, it is also of commercial interest to determine with empirical investigations the pulping potential associated with this type of wood.

It should be noted here, the definition *regeneration cuttings* normally refers to final felling wood from any mature forest stand, which is programmed to be harvested using the clear-cut method. Since the above wood in this study is expected to come only from a naturally regenerated spruce stand of an old age (100–140 years), where no major silvicultural treatments have been made, a better definition would have been *old-growth wood*, and can be used interchangeably. However, as it is an unoffical term with diversified meaning (Hunter 1989), regeneration cuttings was chosen for practical reasons. Thus, in this case, wood from regeneration cuttings means that from a mature natural spruce stand which is fully within a commercial, sustainable forestry, but being rather close to the end of its natural rotation age (see Tapion taskukirja 1991).

Table 14. Matrix of hyphotetical average (assumed limits) wood characteristics in selected pulpwood assortments of southern Finland-grown spruce. Wood is presumed to originate from *Myrtillus* site class.

Wood characteristic	Assortment Sawmill residual wood	Regeneration cuttings	First-thinnings wood
Age-class	60–100	100–140	25–35
Tracheid length, mm	3.3–3.8	2.7–3.2	1.9–2.4
Tracheid diameter, µm	35–41	28–34	20–25
Cell wall thickness, µm	3.6–4.1	3.1–3.7	1.6–2.2
Juvenile wood content, %	0	10–20	50–70
Moisture content, %	60–65	40–50	55–65
Heartwood content, %	0	45–55	5–15
Latewood content, %	22–26	25–30	18–22
Bark content, %	9–11 *	11–13	13–15
Extractives content, %	0.8–1.5	0.8–1.5	1.0–1.7
Knotwood content, %	0.5–2.0 *	0.5–2.0	0.5–2.0
Basic density, kg/m^3	370–400	390–420	360–390

* in sawlogs

Hypothetical values of wood and fiber properties for each three wood assortments are given in Table 14. The presumed average values are derived from the theoretical study and it is quite clear that these values can be only rough approximations, and not definitive because of the extent of variation due to environmental and genetic factors normally occurring in nature. Wood for these assortments is expected to be grown on Myrtillus (MT) site, possessing typical growth rate for southern Finland. These presumptions will be largely tested in empirical part of the study, as most of these the wood and fiber properties will be determined for each assortment.

2.11.3 Obtainable Pulp Properties from Selected Pulpwood Assortments – Hypotheses for the Empirical Study

Table 15 summarizes the expected relative TMP properties, as affected by each raw material assortment, when being pulped separately. For comparative purposes, there is a hyphotetical reference-TMP included. This pulp is thought to be commercial spruce TMP for newsprint, being manufactured from a mixture of fresh sawmill chips, thinnings wood, topwood, and disqualified sawlogs, i.e. normal Finnish pulpwood assortment for thermomechanical pulp. Since there is no average commercial TMP, with respect to mill-to-mill variation caused by process conditions etc., the values for reference-TMP have been derived from several references (see Honkasalo and Ebeling 1981, Vaarasalo et al. 1981, Axelson and Simonson 1983, Malinen 1986, Härkönen et al. 1988, Haikkala et al. 1990, Höglund and Wilhelmsson 1993). In the table, only those pulp properties are included, which are at least partly predictable by wood raw material factors, based on what was found in the theoretical study. If the expected effect is not known or controversial in the literature, the space is left empty.

Table 15. Hyphotetical impacts of various spruce-wood assortments on TMP for newsgrade (about 80–100 ml CSF freeness). Pulp is assumed to be made at constant production conditions from selected pulpwood assortments of southern Finland-grown spruce. The raw-material for the reference-TMP is assumed to be typical Finnish spruce pulpwood.

TMP property	TMP wood assortment Normal wood	Sawmill residual wood	Regener. cuttings wood	First-thinnings wood
Specific energy consumption, MWh/t	1900	–	–	–
Pulp fiber length, mm	1.6	higher	higher	lower
Long fiber content (R30), %	35	higher	same or higher	lower
Fines content (P200), %	27	lower	same	higher
Shives content (Somerville), %	0.15	–	higher	–
Tear index, $mN \cdot m^2/g$	7.5	higher	same or higher	lower
Tensile index, Nm/g	40	–	–	lower
Brightness, % (ISO)	60	–	–	higher
Light scattering coefficent, m^2/kg	57	lower	same	higher

In addition to the following important properties of newsgrade TMP, there are numerous properties, such as burst strength, opacity, sheet bulk and density, sheet roughness and air permeability, which could be included here. However, many of them are largely determined by process conditions or other factors, and cannot be predicted from these wood properties, not even qualitatively. Nevertheless, their determination in empirical study is important, because some significant interactions, being presently not known, with wood assortments might come out, though.

Following hypotheses basing on the critical examination carried out in the theoretical part are being formed here considering the sawmill chips, old-growth wood, and first thinnings as TMP raw materials. These will be tested in this empirical part of the investigation, where each of these three wood assortments will be pulped separately in commercial scale at constant production conditions. Hypotheses are:

1. No significant differences in the TMP specific energy consumption would be expected between each three wood assortment.
2. *Sawmill chips* would produce the strongest TMP which have highest average fiber length, long fiber content, tear strength, and possibly tensile strength, but lowest light scattering properties and fines content.
3. *Regeneration cuttings* wood from old-growth stands would produce TMP with properties falling between the two other pulps, in terms average fiber length, long fiber content, fines content, tear strength, tensile strength, and light scattering properties. Somewhat higher shives content is expected.
4. *First-thinnings wood* would produce clearly weakest pulp in terms of tear and tensile strength, but have highest light scattering and brightness properties. Moreover, it would have highest amount of fines material, but lowest proportion of long fiber and lowest average fiber length.
5. The wood fiber cross-sectional dimensions would transmit to pulp long fiber fractions. Therefore, the printing properties in terms of sheet surface roughness and air permeability, would presumably be best for TMP's manufactured from first-thinnings wood, and poorest from sawmill chips.

3 Comparison between Wood from First Thinnings, Regeneration Cuttings and Sawmill Residuals; a Case Study of Thermomechanical Pulp Manufacture in Mill Scale

3.1 Overview

In preceding sections, the wood and fiber characteristics of Norway spruce and their importance in the manufacture of thermomechanical pulp have been determined basing on available literature. The possible effects caused by wood variables were suggested to be best rationalised in terms of various pulpwood assortments, of which pulping potential might vary accordingly (Section 2.11.2). Finally, hypotheses of the presumed impacts of the most important wood and fiber properties, in terms of obtainable relative TMP properties from these assortments, were formed (Section 2.11.3). The wood assortments are:

- Saw mill residual chips
- Regeneration cuttings (old-growth) wood
- First-thinnings wood

Hereinafter, these three wood origins will be denoted by "SM", "RC", and "FT", respectively. The objectives of the empirical study were already given earlier (Section 1.4).

Perhaps the only reliable and valid way to find out the magnitude and importance of the wood and fiber properties of Norway spruce in the manufacture of thermomechanical pulp (TMP), is to design an experiment of commercial scale. Unlike in chemical pulping, where only a few kilos of wood can be pulped in controlled conditions, laboratory or pilot scale studies simulating mechanical pulp manufacture rarely serve the purpose. Only a commercial scale ensures that industry may use the results obtained with confidence (Levlin and Sundholm 1984, Corson 1991). Moreover, if variation in Norway spruce wood properties is found to be of commercial importance in TMP and derived paper end-products, it means that the operation in terms of forestry, as well as pulp and paper manufacture, has to be feasible not only in theory, but in the real life. In other words, if economical or technical justification exists for raw-material segregation, in forms of improvements in quality and value of marketable production, relevant wood assortments must be kept separately during both forest and wood-handling operations to facilitate the subsequent pulp and papermaking from them.

Case – TMP for newsprint

Höglund and Wilhelmsson (1993), for instance, have emphasized that the product must determine the choise of wood type in TMP manufacture. However, as has been highlighted for several times in this investigation that defining the effects of pulp quality on the quality and properties of a paper end-product, is very complicated and does not always serve the purpose in general sense. Adding the expected impacts of wood variables, firstly on the manufacture and properties of mechanical pulp and secondly, on the paper product subsequently manufactured from this furnish, naturally multiplies the complexity of the task.

Paulapuro and Laamanen (1988) have pointed out that a paper pulp is not generally "good" or "poor". Its papermaking potential always has to be evaluated against its use as a furnish component for a given paper grade. The requirements of different paper grades can vary widely, for example depending on the printing process (Hooper 1988, Hoekstra et al. 1991). So, the suitability of a given pulp may vary considerably depending on the paper grade. Consequently, the papermaking potential or properties of a given pulp have to be evaluated grade by grade. The systematical approach called "product analysis", for searching the requirements set for the paper end product in evaluating papermaking pulps is widely accepted today. Because it is clear that paper will be sold solely based on its functional properties and not on its furnish composition, evaluating requirements for a furnish must thus always base on the identification of these functional paper properties, whereafter the requirements for a paper pulp can be set.

Table 16. General requirements of newsprint and newsgrade TMP as its mechanical pulp component.

Newsprint	Newsgrade TMP sheet
Runnability	high tear index high tensile index low shives content
Printability	high light scattering coefficent high opacity high brightness high smoothness low porosity

In the empirical part of this investigation, *newsprint* was chosen as an end-product for TMP, since the properties of original wood raw-material are definitely most pronounced in this particular paper grade. There are several reasons for that. Namely, the role of mechanical pulp furnish and thus the wood is probably the most important and highlighted in newsprint, since it has the highest proportion of mechanical pulp in its furnish of any wood-containing paper grade, and have only a minimum amount of chemical reinforcement pulp. The amount of chemical pulp vary typically between 5 % and 20 %, depending on component properties relative to end-product requirements. However, it is also possible to manufacture newsprint also from 100 % TMP due to its good strength properties (Jackson 1985, Leask 1987a). In fact, for news grade, spruce TMP represent the most suitable split between optical and strength properties, if the objective is to manufacture news qualities with a minimum addition of chemical pulp (Höglund and Wilhelmsson 1993). Furthermore, there are no fillers, heavy mechanical treatment like super-calendering, or coating, which all change the end-product physical characteristics from the original base sheet in a manner that the properties of pulps might come as secondary.

The main requirements of newsprint can be generally categorized as *runnability* and *printability* of paper (Paulapuro and Laamanen 1988, Saltin and Strand 1992). According to Hooper (1988), the first requirement for newsprint is high strength to achieve runnability. This requires high tear and tensile strength. To accomplish the strength requirements, the pulp furnish must have both a good bonding ability and a sufficent amount of long fibers. Moreover, for runnability the shive level must be low to avoid web breaks, and the surface strength and fiber development must be good to avoid linting. The printability of newsprint is more complex concept, being a function of paper sheet structure and optical properties. For printability the sheet requires smoothness, adequate brightness and opacity, low porosity, and sufficent light scattering properties. The runnability and printability of newsprint against requirements of newsgrade TMP are listed in the above Table 16.

3.2 The Scope and Outline of the Empirical Study

The empirical study is comprised of sub-tasks:

- Procurement of the selected wood assortments for a mill-scale thermomechanical pulping: roundwood for RC and FT raw materials, and sawmill residual chips as SM wood.
- Determination of the average wood properties found to have influence on TMP, and their variation from SM, RC, and FT wood and chips. These wood properties are: wood basic density, moisture, fiber dimensions, latewood content, juvenile wood content, heartwood content, extractives content.
- Thermomechanical pulping of the three wood raw materials at constant process conditions – newsgrade TMP from SM, RC, and FT woods.

- Determination of the important properties in the obtained SM, RC, and FT pulps. These pulp properties are: energy consumption, fiber and particle properties, strength properties, sheet structural properties, optical properties, and extractives content.
- Testing the hypotheses by rationalizing the average wood properties in the SM, RC, and FT wood raw materials in terms of obtained pulp properties in SM, RC, and FT thermomechanical pulps.

The important wood properties that are expected to deviate between SM, RC, and FT type of wood, and have influence on TMP and newsprint, were derived from the theoretical part of this study (see Tables 13–15). It was known, however, that other wood properties than discussed in the theoretical investigation (Chapter 2) can dramatically affect the quality of TMP. Such properties include the amount of knotwood, bark, compression wood, and various wood storage factors. However, they were excluded from the study for the following reasons. Namely, there are expected to be only small differences in knotwood content between the screened SM, RC, and FT accept chips and consequent effects on TMP. The reliable estimation of compression wood, either from wood chips or tree stems is difficult, and, since the compression wood in trees is caused by environmental factors, this property is not specific to any of the selected wood assortments. Bark content, on the other hand, is known to vary typically between the selected wood raw materials, but since TMP requires almost "bark-free" chips, its amount is usually brought close to zero prior to pulping by effective bark removal. To affirm the above, it was necessary to determine bark content from TMP chips. Finally, only totally healthy trees or wood logs are qualified in the manufacture of mechanical pulps. Decayed wood or wood that has color defects (early stage of fungus decay) are not allowed in pulpwood according to the Finnish wood assortment specifications. To fulfill this requirement, decayed stems and logs were removed from the process either in woodland or woodyard operations, before chipping. Furthermore, wood was not stored more than a few days after felling and being pulped.

In order to obtain an understanding of the significance of the selected wood factors in TMP manufacture, a commercial, mill-scale thermomechanical pulping was arranged. In terms of the pulping and procurement of needed wood assortments, this project was a co-operative effort between Enso Publication Papers division (Enso Gutzeit Oy) and the University of Helsinki, department of Forest Resource Management. This part of the study was carried out at EPP Varkaus TMP mill and EG Forest Department, Varkaus Wood Procurement District. Three series of thermomechanical refining was performed in this study, namely for SM, RC, and FT raw-materials. The properties of newsgrade pulps were tested according to standard procedures used in industry. The results obtained were then rationalised in terms of intrinsic wood characteristics of each raw material type and the employed pulping mechanism. However, properties of manufactured paper, that is, newsprint, were not measured since there are numerous variables on the paper machine influencing on end-product and not only pulp furnish used. Detailed description of a project and arrangement of the task is found in the next section (Section 3.3). In the following figure (Figure 36), a framework is shown describing the empirical study layout.

3.3 Materials and Methods

3.3.1 Wood Raw-Material for Pulping Trials

The material for this investigation, consisted of sawmill chips (SM), wood from regeneration cuttings (RC) and wood from first-thinnings (FT), to be pulped thermo-mechanically. The quantity of wood raw-material obtained for each three category was approximately 4000 cubic meters in wood chips, equaling about 1500 cubic meters of roundwood (w/o bark). It was targeted to meet the wood requirement for at least one-day (or 24 hours) pulp production, which normally range between 400 to 550 tons of bone dry pulp. This can be considered sufficiently large quantity of wood to be converted to pulp, in terms of fulfilling the requirements of a mill-scale refining trial. The corresponding chip consumption at the Varkaus TMP plant is approximately 430 to 590 tons (o.d. wood), respectively. As a whole the obtained wood volume in chips totaled up to 12000 m^3.

Experiments were carried out in winter 1993, in the months of November and December. This was firstly so in purpose to prevent all kinds of wood deterioration occurring during other seasons and secondly, the access with forest machinery to the first-thinnings sites was not possible before soil surface was permanently in frozen state. Moreover, the above sequence of felling during the tree dormant season was chosen also to avoid the systematic bias – on both wood for pulping trials and sample trees – due to seasonal variation in sapwood moisture and chemistry (see e.g. Erickson 1979, Parham 1983a). For each pulping trial, the time period from the woodlands and woodroom operations to finished pulps was no longer than ten days.

All localities for wood procurement were situated in southeastern Finland, within 50 kilometers distance from Enso-Gutzeit Oy Varkaus mills, of which geographical location is 62°15´, of northern latitude and 28°00´, of eastern longitude (see Fig. 37). Height above sea level varied approximately between 90 and 110 meters. Before the preparation of wood for pulping, sample trees were taken and wood sample procurement was carried out, for the wood properties determination. This is discussed in later section (Section 3.3.2).

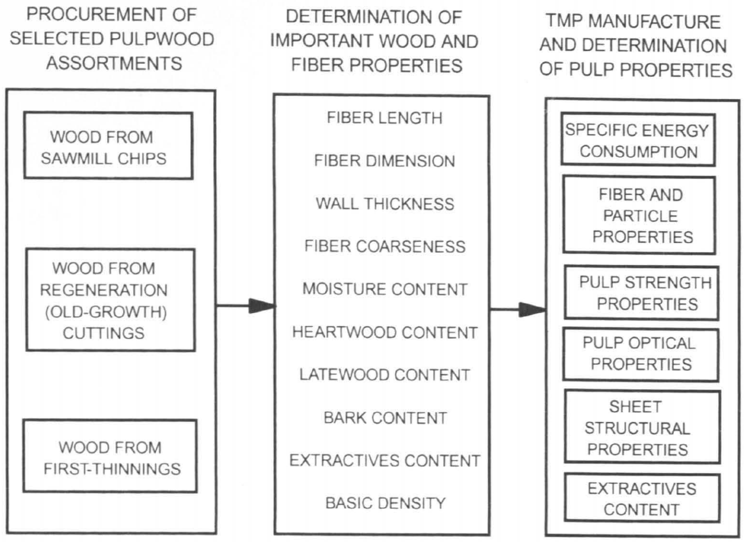


Figure 36. Framework for operationalizations in empirical study – a mill-scale thermomechanical pulp manufacture from selected wood assortments.

3.3.1.1 Site and Stand Selection

In selection of the stands, there were several main principles. Firstly, the wood to be pulped must represent company´s wood procurement area and raw material flow. As described later in this section (see also Section 2.11.2), some age limitations were set for both first-thinnings and regeneration cuttings stands. Secondly, the quantity of wood from each raw material type must be sufficient to quarantee a commercial scale pulping trials. Thirdly, in purpose to lessen the between-stands variation in pulping properties, wood for each pulping sample must come from several forest stands. Moreover, to minimize the effect of growing site on the wood properties, stands must originate from a similar site-class. Small average stand size and company´s harvesting plan with respect to the season were the main limitations in the stand selection. It should be pointed out that EG Varkaus TMP mill uses only fresh wood for its process.

Enso-Gutzeit Oy Varkaus mills and its Wood Procurement District, are situated in an area where Norway spruce typically forms pure, single-species forest stands, being the main wood species in a relatively large area (Sirainen 1995). Elsewhere, outside this "spruce area", it is the Scots pine (*Pi-*

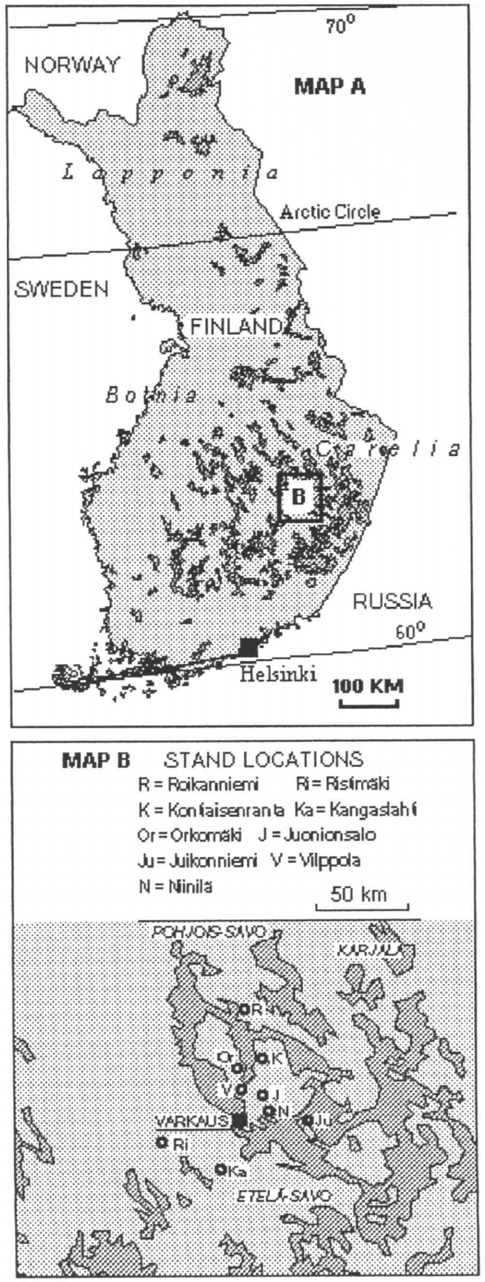


Figure 37. Geographical location of Norway spruce stands for pulpwood procurement and collection of sample trees. A. Index map of Finland. B. Location of forest stands in the vicinity of EG Varkaus Mills.

Table 17. Stand characteristics and wood volumetric data of the Norway spruce stands used in the study. All stands were situated on MT-site (good) type.

Location of stand	Stand size, hectares	Mean stand age, years	Mean annual ring width at DBH, mm	Mean DBH, cm (w/o bark)	Mean tree length, m	Mean length of merchantable stem, m	Basal area per hectare, m²	Average stem volume, l	Number of stems per hectare	Number of stems removed per hectare	Standing volume per hectare, m³/ha	Removed volume per hectare, m³/ha	Removed total wood volume, m
Regeneration cuttings (RC):													
Kontiaisenranta	2.3	105	1.32	26	19.2	14.6	22	317	715	715	227	227	522
Kangaslahti	2.5	95	1.49	30	24.1	18.9	24	495	545	545	270	270	674
Ristimäki	2.3	127	1.02	27	21.0	17.2	24	403	608	608	245	245	564
First-thinnings (FT):													
Juonionsalo	7.3	36	1.44	10	11.2	6.5	30	64	1900	840	102	54	394
Niinilä	2.2	32	2.05	13	12.3	8.1	28	84	1650	550	132	47	104
Vilppola	1.9	39	1.39	10	9.8	5.8	20	52	2005	1005	95	52	99
Roikanniemi	3.4	32	2.03	13	11.2	6.8	30	80	1657	670	136	54	184
Orkomäki	9.6	41	1.73	13	15.7	10.3	34	92	1600	587	141	55	528

nus sylvestris) which is the dominant conifer, growing primarily on poorer and dryer sites. Therefore this area, densely forested with Norway spruce, was ideal for this investigation. The wood for sapwood chips from saw logs, originated also from this area. EG Forestry Department supplies the company's Varkaus Sawmill with saw logs that are acquired from the near vicinity. In fact, 100 % of mill's sawn goods production consists of whitewood, i.e. Norway spruce.

Three localities of regeneration cut (RC) forest and five localities representing the first-thinnings (FT) stands were chosen to obtain sufficient amount of raw-material for pulping, and for wood sample procurement (see Tables 17 and 20, and Fig. 39). As pointed out earlier, the obtained wood volume for each group (SM, RC and FT), approximately 1500 m³ as expressed in roundwood, was firstly fixed for the sake of process conditions and requirements. Consequently, the unit size of the samples to be pulped, was also considered to be large enough in order to obtain a representative sample from each type of wood raw-material, as long as proper selection practice is employed. In other words, a sufficent amount of wood from several stands must be chosen to minimize the normal random variation, related mainly to tree age and environmental factors that occurs in the wood and fiber properties of Norway spruce. A lesser amount of wood, can easily bring up some of that random variation, which is sometimes the case in laboratory- and pilot-scale investigations. Selecting several stands for each category was not for comparison for their similarity in terms of age, spacing, diameter, or in some wood and fiber property, but to get more reliable mean values within each raw-material group. The obtained wood volumes from each stand are presented in Table 17.

Localities of *Myrtillus* site type (or MT-type), were chosen for this investigation, since it represents the most typical combination of soil fertility for this species in southern Finland and this particular area. This forest site classification introduced by Cajander (1909), bases on site's field and ground layer vegetation as indicators. All stands included to the investigation, were on mineral soils (podzol), the main soil type being sand moraine. Stands were selected from those stands, programmed for harvest in November and December, together with EG experienced foresters. Necessary information and data on stand characteristics were provided by company's forest management plan.

As already discussed earlier (see Section 2.11.2) The regeneration cut stands (RC) were intentionally aimed to represent rather the oldest and slowliest-grown end of stands within this category, but yet not being "over-mature" wood. Correspondingly, the stands selected as first-thinnings (FT) stands, were rather of somewhat younger and faster-grown type than an average stand to be selected. This philosophy was followed to segregate the raw-material into as distinctly different groups as possible (RC, FT and SM), in terms of wood properties variation, but so that it could still be feasible in practice, that is, in woodlands and mill operations. Furthermore, concluding all of the above, it means, at least hyphothetically, that if the pulping conditions are identical for each trial, most of the pulp properties variation can be attributed to wood variables, i.e. the three types of raw-materials.

3.3.1.2 Stand Characteristics

Most of the stand characteristics data were readily available in EG Forestry Department computerized database, which system is automatically being kept updated according to predicted annual tree growth. Moreover, every stand programmed for harvesting had a company cutting plan. To confirm and complete available information a few relascope sample plots (1 per ha) were taken from each stand (Tapion taskukirja 1991). Average stand characteristics and some harvesting data can be seen in Table 17. It should be noted that the stem diameter frequency distribution series were not available.

The average age of RC stands, calculated as the number of butt-disc annual increments added with 5 years (shoot development), varied between 95 and 127 years, and that for FT stands varied from 32 to 39 years, respectively. The ring width as such does not influence the quantity and quality of the fibers, but on the basis of this characteristics, information can be gained concerning wood properties important from the viewpoint of pulp and paper technology, such as the percentage of latewood, or wood basic density. It is true, though, that width of annual rings has only little meaning as an indicator of wood properties, and moreover, only within a limited range of ring widths (Panshin et al. 1980, Zobel and Buijtenen, van 1989). As discussed earlier, in theoretical part (Section 2.2.1), juvenile wood near the pith, or overmature sapwood near cambium, can have very narrow rings but also very low density. However, the knowledge of the average ring width helps to form a general picture of the local conditions and the structure of wood, used in this study. Wood basic density and latewood content for wood from RC, FT and SM are reported along with results (Section 3.4.1), as wood variables or pulpwood properties, but not as stand characteristics.

For the regeneration cut stands, the average ring width at breast hight, was 1.28 mm, and that for first-thinnings stands was considerably greater, being 1.71 mm, respectively. This is indicative faster average relative diameter growth for the latter. In fact, with respect to obtained wood volumes from each locality to the mill, this difference is even greater between the RC and FT wood raw-materials. In terms of growing conditions, the regeneration cut stands could be well called as "natural stands", whereas the first-thinnings stands has been relatively more under silvicultural control. Average ring widths for the spruce stands chosen for this study can be considered as typical values in this geographical area. Hakkila (1969) found the weighted mean for the width of annual increments of Norway spruce in southern Finland being 1.5 mm. This extensive investigation was made for pulpwood bolts.

The average tree heights, breast diameters, stem volumes and other stand properties for both clear-cut (RC), and first-thinnings (FT) stands show just natural variation that occur between southern Finland-grown Norway spruce stands with respect to stand age and site fertility class (Tapion Taskukirja 1991). Due to the fact that some of the measurements of stand properties are based on the tree samples procured from each stand, and others on the total roundwood material transported to mill, some dissimilarities or oddities may occur between the values.

In first-thinnings stands (FT), the used thinning method was a *selective thinning from below*, following the normal practice applied in southern Finland (Tapion taskukirja 1991). The above means that dominating (more vigorously grown) and supressed (slowly-grown) stems have a higher probability to be chosen than an average-sized tree. In commercial thinnings, the stands should consist of a certain number of even-sized stems after thinning due to the requirement of stand homogenity (to maximize volume growth). Thus, the characteristics of the removed stems inevitably deviate somewhat from those being left standing. However, it is true that a certain number of larger, dominating trees of poor quality are always being removed as is the case with *quality thinning*. In RC-stands, however, the standing volume consisted of both dominant and supressed trees.

3.3.1.3 Saw-Mill Residual Chips – Procurement and Characteristics

As already mentioned earlier (Section 3.3.1.1), equal amount of wood, than obtained for the two other raw-material categories, i.e., about 4000 cubic meters of spruce chips per pulping trial, was supplied from the adjacent company sawmill. Outer parts of spruce sawlogs, consisting therefore of almost purely sapwood, are normally being chipped, and chips being then sold as a sawmilling by-product to company TMP plant. Approximately 4000 cubic meters (w/o bark) of AB-quality class saw logs were processed for solid wood products, that is, sawn goods, to obtain 4000 cubic meters of chips for the pulping study. This corresponded to approximately three-day lumber production. The ratio of consumed log volume to obtained sawngoods volume varied between 1.8 and 3.1, the average being 2.2. Characteristics of this wood material was aimed to be representative of normal chip production under usual sawing conditions.

Sawmill chips were manufactured from freshly-cut saw logs, right before and through the pulping trial. Chipping was carried out mainly with Ahlström PH700 chipping headrigs. A small percentage of chips were produced with edge-chippers (Ahlström SK2 and SK6). Purchased chips from other saw-mills, which usually constitute a minor part of the chip flow from sawmill to TMP plant, were intentionally excluded herefrom for the purpose of controlling the wood source in terms of its uniformity. Furthermore, no floated (water-transport) logs were accepted for sawmilling during the sawmill chips procurement, because of occational coloring problems (Pennanen et al. 1993). The origin of wood raw-material for the chip procurement, as expressed by forest site and stand data, was not determined in this investigation. However, the data from processed sawlogs, wherefrom the TMP chips (SM) were produced, was available in terms of log quality-classes and dimensions. Table 18 shows data, e.g. on average log characteristics, obtained from sawmilling during the TMP chip procurement. The wood and fiber properties of saw mill chips are presented together with those of roundwoods in later chapter (Section 3.4.1).

Table 18. Data from Norway spruce saw logs wherefrom the residual chips were produced for thermomechanical pulping trial.

Saw log quality class	AB (for all logs)
Consumed saw log volume to sawngoods volume ratio	2.2:1 (1.8:1–3.2:1)
Average log unit volume, dm^3	247 (132–610)
Average log top diameter, mm	250 (135–300)
Average log length, m	5.1 (3.6–6.2)

(Minimum and maximum values of the property shown in brackets)

As in the case of thinnings wood (FT) and wood from regeneration cuttings (RC) procurement, the sawlogs were also supplied by the EG Forest Department, within the Varkaus Procurement District. Company sawlog assortments consists mainly of either butt or the middle logs, but very rarely, if at all, the toplogs. Wood raw-material used for sawmilling (and chipping) originated from the same geographically distinct region than roundwood obtained for two other pulping trials. Moreover, logs came from several different forest stands and locations, the fact that significantly diminishes the random variation in wood and fiber properties of the raw-material in question. All spruce stands programmed and scheduled for harvesting to supply the sawmill prior to the trials were intentionally MT-type stands. This site type is the dominating site for Norway spruce in that area, especially for obtaining sawlogs of this size and quality. However, a possibility that a small part of the sawlogs used for the study came from other site types, always remain there. It should be mentioned that the relatively high average ring with (1.58 mm), measured from sawmill chips (Table 17), suggest good growth pattern in the outer parts of those saw logs used for study (see e.g. Hakkila 1969).

3.3.1.4 Preparation of Wood for Pulping

Harvesting and Transport

A clear-cut with a forest processor or forwarder equipped with a felling head was used as the felling method for RC stands. In FT sites, both manual harvesting and the latter type of mechanized harvesting was employed. Manual thinning operation is usually recommended for first-thinning spruce stands, since there is a great risk to wound the remaining trees, especially if heavy machinery is used. Trees were cut and delimbed according to company rules. The smallest top-end diameter for a merchantable bolt was 7 cm under bark and the stems were cut to 5-meter-long logs. Rotten stem parts were disqualified as TMP pulpwood. Since all felled stems were classified as pulpwood in this study, sorting the bolts different assortments was found as unnecessary. For all sites, the first transportation stage, i.e. from the logging site to road-side storage, was carried out with a forwarder. The second transportation stage, that is, from the road-side stack to the mill gate, was carried out with company trucks. Organizing a relatively large quantity of wood from different locations for the trial, with more or less just-on-time basis, required very much planning in advance.

Woodyard and Woodroom Operations

Prior to the refining trials, one week at most, logs from each particular wood raw-material group were received, unloaded and metered at EG Varkaus mill's woodyard. Furthermore, they were put into a land storage and kept separately from other pulpwoods, that is, wood for kraft pulps, groundwood, chemimechanical pulps, and most importantly, the TMP wood flow.

The above wood-handling was carried out, with the exemption of sawlogs. Saw log procurement and the origin of sawmill chips as a by-product was explained earlier. In fact, even though no floated wood was accepted for the study, all saw-logs must go through the company water-sorting station, which actually means a short term (a few days) water storage. This was not supposed to affect the quality of chips (Pennanen et al. 1993), and moreover, it represents the normal wood flow at EG Varkaus mills. Debarking of the sawlogs, from which the pulpmill's supply of sawmill chips were made, was performed with sawmill's mechanical Valon kone 620 and 820 ring debarker units. Chipping was already described earlier in this section. The screening of the SM chips were under the control of the EG Varkaus sawmill, being carried out with KoneWood screen. After sawmill's chip silo of 5000 m^3 was discharged and emptied from other chips, the SM chips for the trial were subsequently blown pneumatically into this storage.

Reclaimed from the land storage, log bunches were dumped to infeed (or merchandising) decks using mobile log stackers. Prior to being conveyed for debarking system, they went through multiple saw slasher unit, which cut or "slashed" logs to shortwood that fit better into subsequent conveying, debarking, chipping and other process equipment. Oversized logs, i.e., over 60 cm in butt-end diameter, were sorted out from TMP raw-material. Debarking was carried out in one of mill's four rotary drum debarking units (Högfors-Sento), as a dry-debarking process. Debarked logs were then washed and detected from metals before they entered the chipper throat.

The chipping equipment, used mainly for TMP chip manufacture, was a disc-chipper of its design (Ahlström). Chip preparation for TMP pulping included chip screening using a Ahlström gyratory suspended flat screen to remove over- and under sized particles, knots etc. The size of a single chip particle can roughly be characterized by its length, width and thickness. A sample of chips can be characterized by its particle size distribution. This was done by employing the automated screen unit, a Gradex particle size analyzer. As already mentioned in the scope of the study, Chapter 3.2, one major objective in this pulping trial was to eliminate the effect of process variables, such as production rate or process temperature, in order to attribute the pulp quality variations to wood variables. An even chip size distribution between the three woods, although being rather a raw-material property, served too this purpose. The break-down of different size classes for TMP chips at EG Varkaus mills is shown in Table 19. The obtained chip size distributions of screened chips for the refining trials (SM, RC and FT chips) are presented in later chapter of this study (Chapter 3.3.3.1), along with TMP manufacture.

Table 19. Screening of TMP chips at EG Varkaus mills. Target chip size distribution and bark content after chip classifier.

Size class	Retained on screen	Target distribution, %
Overlength	+45 mm	<0.3
Overthick	45/R8	< 7.5
Accepts	**R8/13**	**Total**
Accepts	**13/7**	**>85.0**
Pin chips	7/3	<7.5
Fines	–3 mm	<0.5
(undersize)	(i.e. caught in pan)	
Bark in chips	–	<0.3

Unlike chips for chemical pulping processes at EG Varkaus mills, no outside chip piles are used for screened chips. In the case of TMP, which has rather tight requirements in terms of wood quality (Nyblom 1979, Fuller 1983, Hartler 1985, Leask 1987a), the principle is to convert roundwood directly into screened chips and for subsequent refining. Oversize chips, removed in screening, are rechipped and sent back into the system. At the TMP plant, only a 4000 m^3 chip silo is used, as a buffer-storage and a mixing equipment of chips from different origins. During normal pulping operations, a mix of approximately 60 % sawmill chips and of 40 % roundwood chips, is continuously maintained at the discharge screws of this twin-silo, before chips enter the TMP process (see Fig. 41). For this investigation, one part of the silo had to be emptied in advance from other materials for each pulping trial, to allow a pure supply of chip raw-material in question.

The flowsheet of wood and chip preparation, obtaining TMP chips for the three industrial-scale pulping trials, is shown in the following figure (Fig. 38).

Table 20. Information of sample trees.

Stand type and location	Number of sampled trees	Mean tree length, m	Mean crown ratio, %	Mean DBH w/ bark, cm	Mean tree age, years
Regeneration cut stands (RC):					
Kontiaisenranta	10	19.2	46.4	29.5	105
Kangaslahti	10	24.1	71.6	30.7	91
Ristimäki	10	21.0	65.7	27.2	134
First-thinnings stands (FT):					
Juonionsalo	10	11.1	82.5	10.9	37
Niinilä	10	12.3	76.0	13.6	32
Vilppola	10	9.8	69.8	11.1	40
Roikanniemi	10	11.2	80.5	13.7	32
Orkomäki	10	15.7	73.2	14.1	41

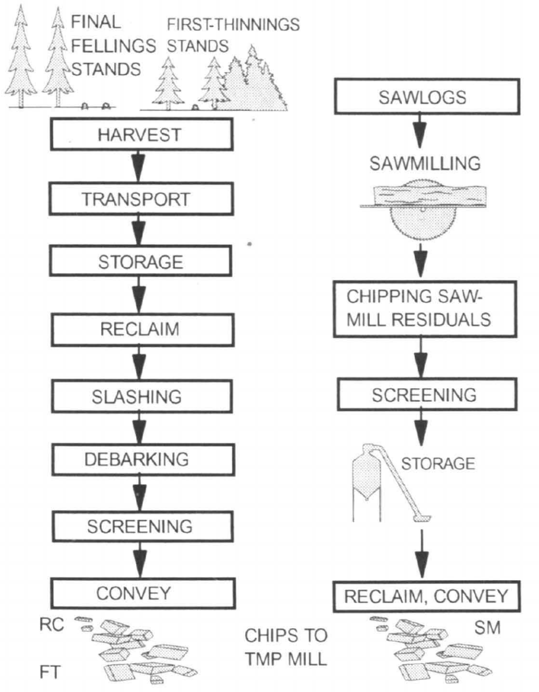


Figure 38. Basic fiber raw material flow to EG Varkaus TMP mill. Procurement and preparation of the three different wood raw-materials for industrial-scale pulping trials.

3.3.2 Wood Properties Determination

3.3.2.1 Wood Samples

In this investigation, the three lots of wood, the SM, RC and FT chips, formed the raw materials for mill-scale pulping trials. However, the goal of this study was not to determine the properties of pulpwood of a certain locality, nor the variation patterns within and between the stands or stems, but simply to establish data on important wood raw-material properties as they occured in the wood flow for TMP furnish. Besides giving a sufficent description of the wood used in the study, the wood properties determination aimed secondly to collect data on these properties for wood from similar conditions, i.e. corresponding assortments of southern Finland-grown Norway spruce.

An estimate of average wood properties and their variation in the population can be achieved only by determining the wood properties (or wood variables) using proper samples and techniques of analysis. Sampling methods and systems for fiber raw material (wood) require more careful design than those for most bulk materials, because its inherent variability is higher. As already discussed in the theoretical part of the study, this variability exists in all fundamental properties, and has its source in the trees themselves.

In terms of sample representativeness, the ideal case in this study would have been to take all necessary measurements and determinations of the wood properties from the chip flow just prior to refining. This was more or less the aim of the

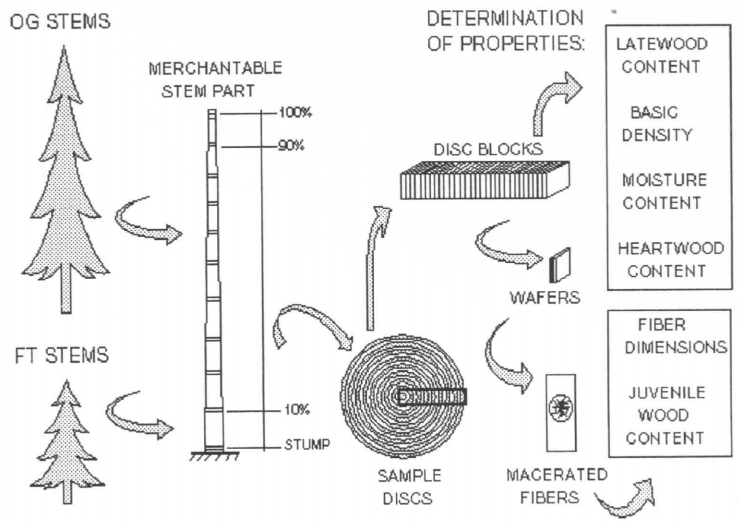


Figure 39. A schematic picture of the sample procurement for wood properties determination from roundwood discs.

sample procurement design. However, it is difficult or just impossible to determine correctly all basic wood properties directly from chip samples. Such wood properties, that can influence on pulping or end-product quality, include for instance the heartwood and juvenile wood content. Therefore, two principal sampling methods were employed – *discs cut from sample trees* collected from different RC and FT forest stands and *chip samples* from all three wood types (SM, RC and FT). Sawing a disc from the stem instead of taking a core with the increment bore was chosen as a sampling method, since it gives much greater accuracy for the required wood properties determination. This is because the disc is many times the size of a core and in it the inner and outer parts of the stem are weighted in exactly the correct ratio (Ericson 1959, Hakkila 1966).

Ten *sample trees* from each Norway spruce stand were carefully selected, felled and discs taken out for determination of *heartwood, summerwood* and *juvenile wood contents*. These sample trees were chosen as follows. In each stand, the stem diameter frequency series of sample trees were proportioned to that of predicted outturn. For instance, in the first-thinnings stands (FT), the sample trees were selected and cut from those to be thinned, since the characteristics of trees are usually left growing and those to be removed can differ somewhat. An effort was made to get sample trees randomly from all over the stand area, and not just the adjacent trees. However, due to very tight quality requirements for thermomechanical pulp (TMP), actual selection had to be more or less subjective. All trees selected, viz. 80 stems altogether, were normally developed and free from rot or other defects. In each locality, sample trees were selected and cut just prior to final harvest of the plot.

Correspondingly, determination of the *wood basic density, moisture content, bark content, extractives content, fiber properties* and *chip configuration* were done from chip samples. Since it was known that in saw mill chips, made out of sapwood of large spruce logs, juvenile wood and heartwood is practically nonexistent, measuring them was found as unnecessary.

Sample Procurement – Discs

From each freshly-cut sample tree, about 3-cm-thick trunk discs were taken out with a chain-saw right after felling. The first disc was cut at the stump height and the others at the same distances up the trunk in length sections equal to 10 % of the length (except the bypass of knots) of the merchantable stem – up to 7 cm minimum top diameter (w/o bark). At first, after sample encoding, the underbark diameter of each disc was determined as an average from two opposite measurements. Also measurements were carried out for heartwood determination, as described later (3.3.2.2). The discs collected in this way – 110 from each locality – were all free from heart or butt rot, sometimes typical for Norway spruce. They were then sealed in double plastic bags and kept in a freezer, in order to prevent any wood deterioration, moisture movements and extractives loss, until they were treated in the laboratory (see e.g. Hakkila 1968).

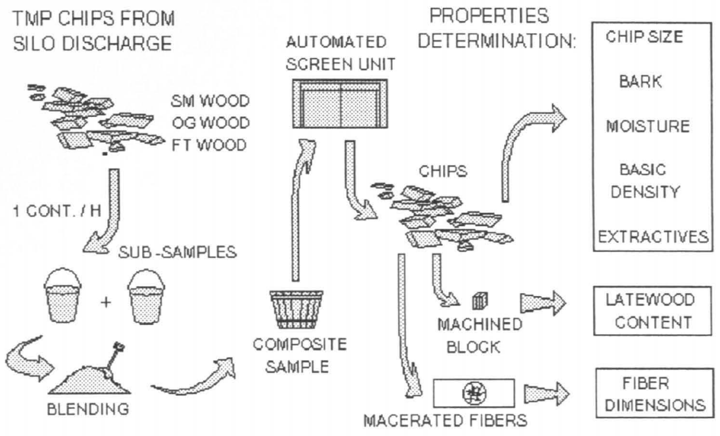


Figure 40. Sample procurement of wood chips and principle for determination of wood properties.

One section sample, always including the tree pith, was cut with laboratory band-saw, from each trunk disc, from random compass direction (see Fig. 39). To facilitate growth ring analysis, basic density and latewood determination, rough cross-sectional faces were smoothed with sanding-machine. From these section samples – totaling up to 880 – specified fiber sections (ring blocks) were obtained later by dividing them into individual fiber sections from the pith and out towards the bark. These specified growth ring blocks were then macerated and used to determine the amount amount of juvenile wood.

Sample Procurement – Wood Chips

In any pulping operation, a chip sampling program is an important part of mill operation and overall product quality. The basic goal of a fiber raw material quality program is to detect quality changes and signal a need for action when these changes exceed predetermined statistical limits. Essential components of the program are therefore sampling, testing methods, statistical analysis, and reporting. In a typical pulp mill, routine chip sampling and testing is carried out daily upon the chip screening operation. Samples are usually taken from a chip stream by using one of the variety of hand-held containers. This is also the case at EG Varkaus TMP plant. Sampling of saw mill chips is done, however, normally from the saw mill's buffer silo, before chips are blown into TMP mill's twin-silo. In Nordic countries, the Testing Committee for Scandinavian Pulp, Paper, and Board has approved standard methods (SCAN) for testing chips. In practice, most companies tend to modify these methods somewhat to suit local circumstances while preserving the essential aspects.

During this investigation – the three pulping trials – the lay-out of chip sampling for wood properties determination was designed and basically carried out following the same principles, but with the exception that samples were taken directly from the chip silo discharge, and not from the chip screens. Naturally, the sampling frequency had to be also multiplied, in order to get a representative samples from each raw-material. Fig. 40 shows the principle in sample procurement for wood and fiber properties determination from chips. The chip

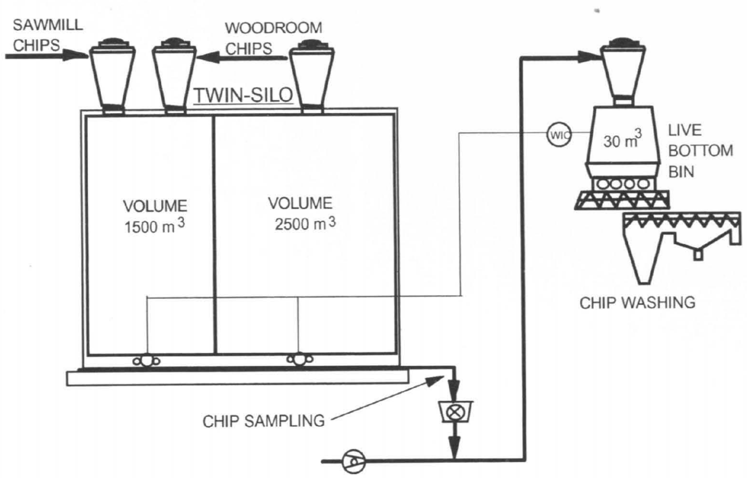


Figure 41. EG Varkaus TMP chip storing system with two adjacent separate compartments. The sampling point for wood chips in pulping trials is marked with an arrow.

sampling location at belt transfer conveyor prior to chip washing can be seen from Fig. 41.

A 12-liter hand-held container was used to take the sub-samples – one in every our. Thus, if a refining – trial lasted 25 hours, for example, the same amount of sub-samples were collected. Subsampling and blending (or compositing) prior testing is normally expected to result in representative sampling. In this case, a composite sample was prepared out of each two subsequent subsample, for laboratory screening (chip particle size distribution), and determination of moisture and bark content. These had to be carried out immediately after sampling to avoid drying and wood deterioration. From the composite samples, also sets of chip samples were prepared for chip thickness and length measurements. For other wood property determinations – wood basic density, extractives content, and finally the anatomy of fibers – appropriate composite samples were made by collecting chips from all original sub-samples.

3.3.2.2 Analysis

Definitions for important Norway spruce wood and fiber properties, and their determination, commonly used in wood science, were already discussed thoroughly in the theoretical part of this study (Chapter 2).

As mentioned in the preceding section (Section 3.3.1.4), chip size distribution were automatically determined from the composite samples, along with measurement of moisture and bark contents. Six parallel set of tests were carried out from each, employing a Gradex automated screen unit. SCAN-CM 40:88 standard method were followed in testing. Since no recent Scandinavian standard method is available for average chip dimensions analysis, it was decided to measure the average chip length and thickness – 100 chips from each composite sample – in laboratory by hand with precision ruler. Average chip properties of the used chips and their variation are described later, in Section 3.3.3.1 along with conditions of TMP manufacture, used in trials.

Wood Basic Density

The most commonly applied methods of determining wood density is by measuring separately the weight and volume of the sample. In this case, the *water displacement method* (see Ericson 1966) was chosen as it is fast and accurate method of determining the green volume of relatively small wood samples, and suggested also for chips (Olesen 1971, Fuller 1987). This method has been earlier successively used by Nylinder (1953b, Hakkila 1966, Olesen 1976) for Norway spruce. To obtain the maximum swollen state, i.e., moisture content above the EMC, the samples were soaked in water (at least for 24 hours) until they sank, before volume measurement. It has been shown earlier that soaked samples give practically the same accuracy as green ones (Ericson 1966, Hakkila 1966). The mass of oven-dry, unextracted wood were determined by weighing. The oven-dry weight was obtained by drying the wood samples several days in a conditioned laboratory oven, at 103°C temperature. No effort, however, was made in the present work to remove the extractives prior to determination of basic density, as the removal of such amounts cannot appreciably increase the accuracy of using basic density as an indicator of pulpwood quality (Hakkila 1966). Basic density was also measured on the disc section samples using the SCAN CM 43:89 standard method, in order to compare that with values obtained from chips.

Moisture Content

For determination of wood MC_w, the mass of green chip samples were measured by weighing. Thereafter, the same lot of chips was put into a conditioned laboratory-oven, and kept there for 24 hours at 103°C ±1°. The chips were then weighed again to obtain the mass of o.d. wood. Application of this method is described in detail by several investigators (Jalava 1952, Skaar 1972). The *dry matter* (or solids) *content*, which was also determined (SCAN-CM 39:88), is the wood mass in absolute dry condition in grams of the wood mass in green condition in grams, also expressed in percentage.

Heartwood Content

One advantage of obtaining sample discs during Nordic winter circumstances, is the ease of measuring the radius of heartwood from them, since no staining with chemicals is needed. Unlike pine (*Pinus sylvestris*), which have a distinct macroscopically visible border between darker, extractives-rich heartwood and lighter sapwood, there is no such demarcation line in Norway spruce, except at temperatures below 0 C°. Then, the heartwood zone appears in the exposed cross-cut clearly lighter in colour, whereas sapwood with higher moisture content shows much darker (Trendelenburg 1939).

Since it was of great importance to find out the proportion of heartwood in the TMP raw-material used for pulping trials, it was decided to determine the average volume of heartwood in the sample stems, and not only its width in a stem cross cut, as used in many studies (see Hakkila 1968). In order to get a proper estimate of heartwood volume, the following procedure was carried out. The heartwood widths (radius) and corresponding disc radii were measured from the sample discs as an average value of the two opposite measurements. This data – from 11 discs per each sample tree – was then used to calculate the volume of heartwood in stems. It was known from earlier studies (see Section 2.8) that in Norway spruce, the heartwood content increases from stump up to about 10 % of the tree height where it starts to decrease towards the tip. Mathematical cubic splin-functions, as used by Koivuniemi (1992) in his investigation of Norway spruce heartwood, were used to form a model from the heartwood and sapwood volumes in a stem. This model was compared for its accuracy with stem curves obtained with Metsäteho's computer program. Differences of less than 4 % in the average calculated volumes were found between these two methods. In both models, it was assumed that the tree trunk and the heartwood core is cylindrical in shape.

Juvenile Wood Content

As being obvious from the theoretical study (Section 2.6), the boundary of juvenile wood in the tree cannot be precisely determined, and no explicit methodology therefore exists to determine it. This is because there is no distinct boundary between juvenile and mature wood, but a transition zone, where wood properties change gradually with a certain pattern, and varying though more or less independantly of one another. Being so, juvenile wood is a concept the significance of which depends on the property of greatest concern for the application being considered. Consequently, in the literature, juvenile wood has been defined in several ways and determined using different techniques according to ring age, anatomical differences between juvenile and mature wood fibers, etc. (Boutelje 1968, Thörnqvist 1990, Kucera 1994).

A method which, bases on the foundings of

Kucera (see Section 2.7), was employed here to determine the boundary between juvenile and mature woods in sample trees. Since the pattern for fiber length variation of Picea abies, in radial direction is well established and was known, this property was chosen for further examination. The average tracheid length of separated latewood ring sections from each disc sample, viz. years 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 33, 40, 50, etc., was first determined. For each ring section, the corresponding distance from the pith was registered. Naturally, in the case of samples from young stems or tree tops (low age), the same pattern was followed until the cambium was reached. To separate the fibers from the wood matrix, a mild maceration of the tissue was made using the Franklin's (1945) technique. The fiber length was determined after drying a dilute suspension on a glass plate and projecting an image of the fibers, using a Carl Zeiss Jena projection microscope onto a digitizer pad. Individual projected fibers were then measured with semiautomatic device, i.e. a computer interfaced digitizer. A total of 50 measurements, with an accuracy of 10 µm, was made on the whole tracheids of each growth ring sample. A computed curve, basing on data from each height of a sample tree (separated section samples), was plotted and the juvenile wood boundary was then established where the curve showed a clear inflection point. The volume content of juvenile wood in each tree, were obtained by using the same technique as in the case of heartwood content, described earlier in this section. The average juvenile wood percentage of each stand (weighted by the procured stand volume) formed then the estimate of the average juvenile wood percentage in the whole research material, that is in OG and FT woods.

Latewood Content

In forestry and wood science, the latewood percentage refers usually to the average proportion of latewood in the growth ring of the full growth ring width, expressed in percents. This is probably so, because of the ease of determination from traditional increment core samples. Since substantial variation in latewood width can occur in the radial stem direction, the above mentioned procedure was found insufficent. In this investigation, the latewood content was defined and determined as a volume percentage in the stem. With respect to pulp and paper industries, the most satisfactory way of determination would have been to determine the weight ratio of latewood to earlywood.

For RC and FT woods, latewood content was determined basing on the disc material collected from different heights of the sample trees. The latewood percentage, as well as the ring widths were measured with the aid of Heidenhein ring-width meter. In addition to that, the system was comprised of an Olympus microscope, a Sony video camera, and Lustonmittaus-computer program. The obtained information included the widths of earlywood and latewood in each growth ring, and the corresponding distances and ring number from pith. The radii analysed in the segregated disc sections were chosen so that the effect of knotwood and compression wood was minimized. When the distance of inner and outer boundary of a latewood ring from the pith is known, assuming its shaped as a regular circle, the area of latewood in a stem cross section can be mathemathically calculated. The areas of both earlywood and latewood was computed for each tree height and the volume of latewood then obtained with the same stem form simulation procedure as used in the determination of heartwood and juvenile wood.

Determination of latewood volume from chips is difficult if not impossible, because of small and irregular shape of these particles. In order to get an estimate of this wood property in SM wood (chips), 1000 randomly chosen particles from accepts chips, were machined into cubical or rectangular shaped blocks, in a way that the grain orientation was always perpendicular or parallel with side faces. From each sample, both latewood and earlywood widths were measured. In regular objects as described above, the cubical content of latewood (or earlywood) equals to its cross-sectional width, thus the volume determination was found as unnecessary.

Fiber Morphology

The chip samples were used for fiber dimensional analysis of the three pulping raw materials (RC, FT and SM woods). The amount and frequency of sub-samples and compositing them, as described earlier (Section 3.3.2.1 and Figure 40), aimed to provide representative samples for the wood properties determination. However, the needed amount of wood material for these measurements is quite minimal. Therefore, a small amount of chips – a few kilograms per each type of wood – were picked randomly, one by one, from the composite lots, and divided with a cutting knife into continuously smaller portions in a purpose to obtain wood material from a large number of chip particles for defiberizing by maceration. The used maceration technique was the same as with the juvenile wood determination, described earlier in this section.

Wood *fiber lengths* were determined using a Kajaani FS-200 fiber analyser. Also, it was possible to establish the *fiber length distribution* and *fiber coarseness* data of the examined wood material. An excellent description of the used technique is given by Paavilainen (1993) and is therefore not described here in detail. The fiber lengths obtained in this way include mainly whole tracheids, but also a portion of cut tracheids resulting from the chipping operation. The average fiber length was calculated and expressed as a length-weighted fiber length value, since it places greater emphasis on the number of unbroken, whole tracheids.

Average radial *fiber width, fiber wall thickness* and *lumen size* were measured manually using a Axioplan projection microscope and Kontron Vidas image-analyser. The measuring accuracy was 0.1 µm and the number of fibers used per specimen was 300 or 100, respectively, depending on the sample type. Two types of samples were prepared for the fiber anatomy measurements – a cross-sectional cut and a longitudinal projection, where macerated intact fibers were mounted on slides and measured under polarized light. Since the former sample type is dried and the determinations on the latter specimen occur in wet, saturated condition, the obtained values are not the same. The fibers' propensity to collapse upon drying can also influence on the results. Additional data from fiber dimensions from the separated growth ring sections, was obtained upon the juvenile wood determination.

Extractives Content

In this study, the average amount of *extractives* soluble to DCM (dichloromethane) and ethanol was examined from the wood chips of different origins (RC, FT, SM). However, no chemical analysis was made to determine the quantity and quality of various compounds in extracted material. To determine the average extractives content in wood samples, solvent extraction was carried out for a wood meal ground from chips using Soxhlet apparatus. The method and procedure followed in this investigation, is described in detail in SCAN-C7:62 standard and is largely used the Finnish pulp and paper industry.

Bark Content

Since the aim in TMP chip procurement at EG Varkaus mills is to have as little as possible bark in the screened chips, i.e. less than 0.3 % (o.d. weight), the most efficient bark removal with a minimum wood loss must be carried out in wood and chip preparation in order to avoid deficiencies in end-products. Therefore, measuring the original bark content of roundwood was of no particular interest. Instead of that, the bark content (by weight) was determined from the screened chip samples according to SCAN-CM 42:89 standard procedure. For greater accuracy, also a method suggested by Hakkila and Saikku (1972) was employed on the chips from the blended composite chip samples, described earlier. This manual method has been used among others by Vesisenaho (1993), and allowed accurate examinination the average amounts of inner and outer bark from screened chips.

3.3.3 *TMP Manufacture*

3.3.3.1 Chip Quality

Prior to each pulping trial, in order to assure that the right raw-material arrived to the pulping process just on right time, as well as to get a minimum (if at all) amount of transition pulp from other wood sources, chip silos were first almost emptied from all other chips and subsequently filled with chips in question. 100 % furnish of each wood at a time – SM, RC, or FT chips – was then prepared onto the digester conveyor at the discharge, which is located at the bottom of silo (see Fig. 41). For comparison of chip quality evenness, the results of laboratory chip screening, described in the next section, are presented in Figure 42. More data from chip properties, e.g. average values from each screening and their standard deviation, is also presented in Appendices 1–2.

Mention should be made of the relatively uniform chip quality between each wood type, as expressed with the share of *prime chips (accepts) content* in the furnish, although some deviation within the accept chips, i.e., between the chips retained on 8 mm and 13 mm screens, and overthick- and pin chips fractions, existed. The percentages of prime chips were relatively even between each wood type, viz. 89.3 % for sawmill residual chips (SM), 90.0 % for the chips from regeneration cuttings wood (RC), and 87.8 % for the chips from first-thinnings wood (FT). Moreover, chip size distributions between the three wood types varied in a way that SM raw-material had the greatest overthick fraction, 7.9 %, being slightly off the target specification (< 7.5 %), whereas that of RC wood was only 2.3 %. Moreover, the overlength (or overlarge) chip fraction of FT wood was slightly off the spec (< 0.3 %), being 0.35 %. Otherwise chips from all three wood assortments fall satisfactorily inside the company quality specifications (see Table 19 and Appendices 1–2). The average chip dimensions varied to some extent. Corresponding average chip lengths/ thicknesses, in the same order, were 18.13 mm/4.25 mm, 17.76 mm/3.99 mm, and 15.84 mm/ 3.86 mm, respectively. The content of bark in screened chips was 0.1 % in SM chips, and 0 % in both RC and FT chips.

Chips were washed before they entered the chip preheater bin. The purpose of chip washer is to remove contaminants that sink in water, provided that enough dwell time is allowed for them to separate after chips and water have been mixed. Such contaminants include fine grit and sand particles, which can cause damage to processing equipment and reduce product quality. A secondary function of a chip washer is to introduce water to the chips, especially to dryer heartwood chips. Chips will pick up a some water in the washing process and the increase of moisture content, being usually a few percents, is highly dependable on wood species, dwell time and chip size distribution. Fine particles of wood and bark will also be removed (by filtering-out) by a chip washer, although as much of these fines as possible should be removed by screening. In addition to chip washing, chip cleaning consisted of removal of ferrous-metal objects with a magnet.

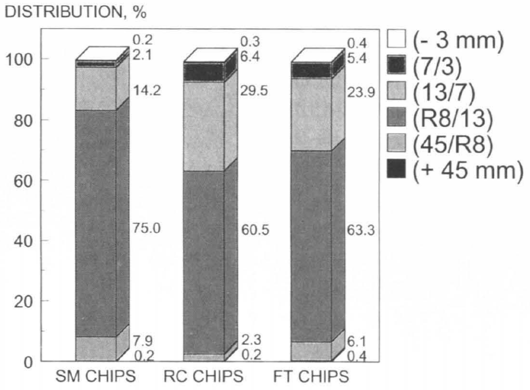


Figure 42. Chip size distributions of the wood raw materials used in pulping trials. SM = Saw mill residual chips, RC = wood from regeneration cuttings, FT = wood from first-thinnings.

3.3.3.2 Refining Strategy

Added with about 5–10 % kraft pulp and a minimum portion of groundwood (< 5 %), TMP forms the major furnish component on the Enso Publication Paper division's two paper machines, PM2 and PM4, of which main end-products are newsprint (standard and special) First of all, the selected refining strategy in pulping trials, not to forget all the other relevant stages in the TMP process, had to be in accordance with and resemble the normal production conditions for manufacturing newsgrade and special newsgrade pulp. This was due to the fact that when paper for a certain customer order – a given grammage and quality specification – is being manufactured in either of these machines, the required rate of TMP production must be maintained to fulfill continuous paper production. In practice, the Varkaus TMP mill have to "sell" or "market" its product to the adjacent paper mill, from the same division. Therefore, any TMP to be manufactured in a trial, must also meet the critical properties of such end-product, in terms of product specification. Moreover, the trial conditions had to be easily reproducible in mill. Data on some target and minimum quality levels for news grade pulp at EPP TMP mill, is shown in Table 21.

Table 21. Data on target and minimum pulp quality in the TMP production at EG Varkaus mill.

TMP	Target	1. alert	2. alert
I-stage			
– consistency, %	32	±4	±7
– freeness (CSF), ml	380	±20	±40
– PQM sum shives, No/g	<4200	>4500	>5000
II-stage			
– consistency, %	32	±3	±5
– freeness (CSF), ml	105	±10	±15
– PQM sum shives, No/g	<1800	>2000	>2300
Latency chest			
– consistency, %	2.8	±0.5	±2
– freeness (CSF), ml	140	±5	±10
Final pulp (latency removed)			
– consistency, %	10	–	±1
– freeness (CSF), ml	75	±5	±10
– PQM sum shives, No/g	<1500	>1600	>1800
– tensile index, Nm/g	>42	<42	<41
– tear index, mN.m^2/g	>8.2	<8.2	<8.0
Refined reject			
– consistency, %	2.8	±0.5	±2
– freeness (CSF), ml	130	±20	±30
Reject refiners 3–5			
– freeness (CSF), ml	110	±20	±30
– PQM sum shives, No/g	<2000	>2300	>2500

The idea of this investigation was to produce pulp from three different, but relatively uniform wood raw materials, in constant production conditions during three trials. However, in mill scale, it is practically a pure impossibility to arrange and control the production variables so that all conditions were equal. On the other hand, there were no intention to fix or arrange ideal process conditions towards a specific raw-material, although it was at least intuitively known that refining these three different raw material with the same plate pattern or in standard conditions, could not produce the optimum result. What comes to refiner plate wear, production rate and pulp quality level, an effort was made to control their evenness between the trials. Since the required fiber composition and amount in a paper machine run largely depends on the paper product in question, an arrangement was made to have a similar end-product, that is, white (non-colored) newsprint of 39 g/m^2 grammage, on paper machine PM4 during all trials.

It should also be mentioned here, that not only in the case of refining, but also all relevant stages of wood conversion – from wood harvesting, and transport to woodyard and woodroom operations – had to be feasible in terms of day-to-day operation, and not cause any drastic or immediate operational changes due to trials.

3.3.3.3 Process Conditions

Varkaus TMP mill, consististing of three independent 2-stage production lines, hereafter referred to as lines A, B and C, were employed for pulping trials. The maximum designed production capacity of the TMP system is 650 oven-dry tons per day. Process descriptions of TMP and other mechanical pulping systems can be found abundantly in literature (Paulapuro et al. 1983, Jackson 1985, Leask 1987b) and therefore not discussed in detail here (see also Fig. 2). However, a schematic diagram of EG Varkaus thermomechanical pulping system is presented in the following figure (Fig. 43).

Each line is composed of 2 double-disc 9.5 MW Sprout-Waldron Twin 50 refiners, of which the primary refining stage is pressurized, the secondary refiner being atmospherical. The TMP process begins from the 4000 m^3 chip storage silo ("twin-silo"). Chips are normally discharged from silo compartments, mixed and fed through to live bottom bin feeding the chip washer (Fig. 41.) followed by a vibra screen for effective dewatering. In the trials, only one silo compartment was used for storing chips. Washed chips are fed by screw conveyors to the three feeder's chip hoppers equipped with bin activators. Plug-screw feeders driven by hydraulic motors press the chips to the preheaters. The chips are steamed in a vertical steaming tube for 2 minutes at 125°C (240 kPa). At the bottom of preheating unit, hydraulically driven, pressurized screws then transport the chips to the two sides of the "Twin 50" refiner. These metering screws have digital speed sensors and closed loop speed control. The refining consist-

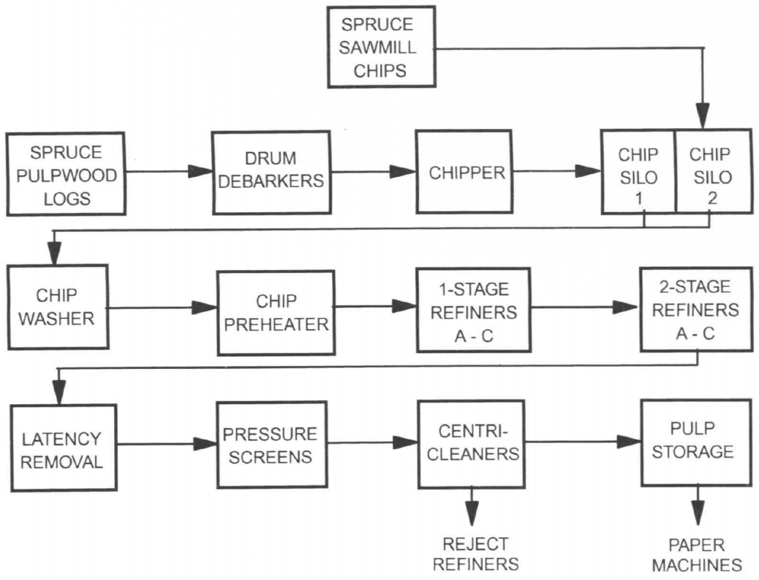


Figure 43. Process flowsheet at Enso-Gutzeit Oy Varkaus TMP plant.

ency after both refining stages is normally 32 %. The steam is recovered from both stages with the aid of pressurized cyclones. After the second-stage refiners, pulp is flushed down into a pit, diluted to 4 % consistency, and pumped into a tank sized to hold the pulp for 60 min for latency removal. Process conditions at the EG Varkaus TMP plant are shown in Table 22.

The latency-free stock is screened by pressure screens in one stage and cleaned in four stages. The stock is then thickened on disc filters and directed either at 4 % consistency into a multichannel chest equivalent to 8 h production or distributed at 10 % in a storage tower, which supplies the paper machine PM4. The combined screen and centricleaner rejects are dewatered by a vacuum filter up to 22 % consistency and refined in five 2.9 MW rejects refiners. The reject rate from the main flow is approximately 25–30 %, the rejects handling being separate from the main flow. The refined rejects are screened separately, but cleaned with the refined pulp. Accept is returned to the main flow. As the brightness and opacity levels of the newsgrade spruce TMP are normally adequate, a bleaching plant is not needed.

Table 22. Process conditions at EG Varkaus TMP mill. Mainline refining consists of three lines – lines A, B, and C.

Chip preheating	
– retention time	2 min
– temperature	120–125°C
– pressure	1.5 bar
1-stage refining	
– refiners	9.5-MW Sprout-Waldron DD Twin 50
– capacity/line	210 t/d
– temperature	saturated steam temperature
– pressure	1.5 bar
– consistency	32%
– plates	Sunds Defibrator Jylhä 19119 56"
2-stage refining	
– refiners	9.5-MW Sprout-Waldron DD Twin 50
– capacity/line	210 t/d
– temperature	appr. 100°C
– pressure	atmospheric
– consistency	32%
– plates	Sund Defibrator Jylhä 19120 56"
Rejects refining	
– refiners	2.9-MW Sprout-Waldron 45 I-B
– rejects rate	appr. 25%
– temperature	appr. 100°C
– pressure	atmospheric
– consistency	22%

3.3.4 Pulp Properties Determination

The pulp yields from each different raw-material – RC, FT, and SM woods – were not determined, since its measurement with the desired accuracy, was found impossible in the used industrial complex. The average TMP yield from Norway spruce wood, varies at EG Varkaus mill normally between 95 and 98 per cents, calculated on annual basis. Pulp power consumption includes the energy consumed in both main line and rejects refining. The pulp specific energy consumption (SEC) is expressed as kilowatts per ton of obtained thermomechanical pulp, based on the oven dry pulp weight. Many of the selected pulp properties for laboratory determination were part of mill's quality control program, because they were considered to be critical from the perspective of newsprint manufacture. Furthermore, it was decided to evaluate some additional properties, which could best describe the different wood raw-material factors in pulp.

3.3.4.1 Pulp Samples

The prerequisite to have uniform production rate between all trials, i.e. pulp from SM, RC and FT woods, was handled by operating the TMP line A (or no. 1) with constant chip and pulp flow conditions, facilitated by its consistency-control system. Therefore, in order to get pulp characteristics and quality data from the first and second refining stages, it was line A wherefrom pulp sampling was arranged. However, to get a sample which would best characterize the newsgrade end-use pulp, samples were taken from a pulp flow after screening and cleaning, but before a storage tank. Thus, this pulp consisted also of the refined rejects. The pulps discussed above, are hereinafter referred to as A_1(1-stage) A_2 (2-stage) and newsgrade pulps, according to the stage of refining and sampling location. Actually each sampling point formed a separate pulp, in terms of testing.

To get representative samples from the production of each trial pulp for the purpose of its properties determination, composite samples were prepared. In other words, a handheld containerfull of pulp was taken every hour from each three sampling points. Four subsequent samples were then blended to obtain a composite sample. For instance, if the refining trial lasted 24 hours, six composite samples were prepared from each three sampling points – A_1, A_2, and newsgrade pulps. The above described sampling was carried out in addition to normal sampling and testing procedure, taking place for quality control's sake, at mill. A large part of the determinations on pulp properties could be done on-site, soon after refining. However, it was necessary to conserve some dewatered pulp samples in a freezer for further evaluations, such as scanning electron and light microscopy, as well as sheet properties analysis.

3.3.4.2 Pulp Evaluation

Analysis of pulp properties was based on standard mill testing procedure, but with extended sampling and various separate laboratory evaluations. In this study, the properties of pulps are grouped into *fiber properties*, *strength properties* and *optical properties*. In addition to the above mentioned groups, the *content of extractives* (DCM) was determined from end-use (newsgrade) pulps using Soxtlet-extraction. A description of this methodology was giver in earlier chapter (Chapter 3.3.2.2) along with wood properties evaluation.

The fiber properties give some idea of particle composition in pulp. Those properties usually form the base for or give rise to many paper properties. When a laboratory sheet is made by dewatering a fiber mat, a fiber network is formed, of which structure is largely influenced by the particle composition of pulp. This sheet structure can give a useful information of pulps ability to form paper webs. Pulp strength and optical properties were determined from dry sheets. Actually sheet consolidation and properties of a paper sheet are related to a large extent to pulp particle properties. Many pulp properties are also interrelated. Strength properties are especially important for web runnability on the paper and printing machine, as well as for end-use applications. Pulp optical properties can contribute good paper printability and end-product appearance. All handsheet properties were determined from sheets made with ordinary sheet former (SCAN-M 5:76), in which the finer material is prone to get away, that is, a poor retention. However, to get a more representative picture especially of the pulp optical properties, additional handsheets were also made with circulating (recycled) white water (SCAN-C 26:76).

All standard procedures of Scandinavian Pulp, Paper and Board Testing Committee (SCAN-standards) and properties determination. Basically, it means that all determinations are made in a certain manner, using a sufficent amount of samples, and in doing so the requirement of statistical significance within the accuracy of measurement can be fulfilled. List of employed SCAN-standards is found in Appendix 3. Most of the methods used in this study, both for the sample preparation and pulp testing, were in accordance with the above mentioned standards, and therefore it is not necessary to discuss of them in detail. However, some methods are either just recently established or appropriate standard does not exist. A greater attention is thus given to these methods of analysis, in this chapter.

Latency, that is, the tendency of TMP fibers to curl after leaving the hot refining zone (d'Clark 1985), was always removed from pulp by hot disintegration (SCAN-M10:77) prior to pulp properties determinations. It should be mentioned, that the composite samples were tested at the freeness "as is", that is, the average CSF freeness value for each 4-hour production period. In mechanical pulps, the freeness value is said to characterize the water removal ability on paper machine and to some extent the pulp quality, and is therefore used as a control variable in pulping. Testing room conditions for handsheets strength and optical properties evaluation were 23°C temperature and 50 % relative air humidity (SCAN-M 8:76).

Pulp strength properties

Laboratory test sheets were prepared from the three trial pulps made from different woods and their physical properties determined, in terms of sheet strength. Prior to the strength properties testing, same samples were used to determine the sheet structural properties, i.e., *grammage, bulk,* and *sheet density*. The same properties, added with measurements for two important properties, viz. *surface roughness* (Bendtsen) and *air permeability* (Bendtsen), were also determined from separate sheets produced with circulating white water. Those two properties characterize the sheet surface and the porosity of the fiber network.

Mechanical pulp strength properties are most often attributed to the shape and proportion of pulp particles (Forgacs 1963, Shallhorn&Karnis 1979, Jackson and Williams 1979, Mohlin 1979 etc.). For instance, two TMP's compared at the same freeness level, can have totally different strength characteristics, resulting from particle properties (Mohlin 1979). Generally, pulp strength properties are a complicated function of the bonding potential of fibers (and fines) in pulp, and the strength of these particles. In this investigation, the determined strength properties were *tear index, burst index, tensile index* and *stretch*. The indexed value refers to a particular strength property, in which the influence of sheet grammage is included, thus facilitating comparisons between sheets of any basis weight. For instance, tensile index is an indication of tensile strength of a dry pulp sheet.

Optical Properties

Mechanical pulps have generally good optical properties compared to chemical pulps, mainly due to the proportion and quality of fines material in these pulps. Also the exposed surfaces of fibers and broken fiber material contribute to free light scattering surfaces in a sheet, giving a paper high brightness and opacity values. Partially therefore, these pulps are preferred in the manufacture of printing and writing papers. The determined optical properties from the trial thermomechanical pulps were pulp *brightness* (ISO), *opacity, light absorbtion coefficent* and *light scattering coefficent*, the last property being independent of paper grammage. The optical properties were determined from test sheets with Elrepho-appliance using 577 nm wavelength for measuring. As already mentioned before (4.2.4.2), two types of test sheets were evaluated. Scattering and absorption coefficents were calculated using the Kubelka-Munk equations (Gupta&Mutton 1967, Lee et al. 1988).

Fiber and Particle Properties

In paper pulps, the *fiber and particle properties* can be a heterogenous concept, that depends largely on purpose of its user. Moreover, what here or elsewhere are called pulp fiber properties, do not necessarily reflect the intrinsic fiber properties of original wood raw-material, since they can be a result of manufacturing process. In mechanical pulps, when their structural composition is characterized, the fiber length and particle size or shape classifications are almost always used. Already early workers, such as Brecht and Holl (1939), Forgacs (1963), Mannström (1967) attributed the most mechanical pulp properties to be dependent on the fiber length and shape factors. Especially, the pulp bonding properties, i.e., the pulp particles' ability to form interfiber hydrogen bonds in a final paper product, are largely a result of fines particles that typically have abundant specific surface. It has also been well proven, that mere freeness value and fiber length distribution, which were a few decades ago thought to be enough when evaluating the stone groundwood, are no more sufficent in present day, and more considerate methods are therefore utilized. This is especially true in the case of TMP, where a large variation in pulp properties is obtainable (Mohlin 1979, Kurdin 1979). In this investigation, the following average properties were determined to characterize the pulp fiber properties:

- pulp particle distribution (Bauer-McNett, PQM)
- shives content (Somerville, PQM)
- shives distribution (PQM)
- average fiber length (Kajaani)
- fiber length distribution (Kajaani)
- fiber coarseness (Kajaani)
- fiber diameter
- cell wall thickness
- lumen size
- latewood content
- fibrillation index
- specific filtration resistance of the middle fraction
- specific sedimentation volume of fines material

The pulps were always disintegrated and fractionated to provide the long fiber fractions for fiber morphology tests. In addition to the above listed properties, the *scanning electron* (SEM) and *light microscopy* were applied to long fiber sections of in order to obtain qualitative data from pulp fibers.

Like in the case of wood samples, optical Kajaani FS-200 fiber analyser was used to determine the *average fiber length, fiber length distribution,* as well as the *fiber coarseness* from pulps. It should be borne in mind, that fiber length distribution, especially in mechanical pulps consists always of two different elements: fibers and fines. In this study, fiber length data from both whole pulps and their long fiber fractions – from Bauer-McNett R14 and 14/28 mesh screens – was obtained. With Kajaani apparatus, the above mentioned fiber properties can be measured easily from a small pulp sample (pulp slurry). The measurement is based on the ability of fibers to change the level of light polarization when they pass through a narrow capillary tube. Basing simply on different computations (computer interface), it is possible to obtain arithmetic, length-weighted and weight-weighted average fiber lengths with Kajaani apparatus.

Determination of the fiber coarseness, a measure of cell wall mass per fiber length (mg/m), was included to pulp analysis. Although it is not, by all means, a measure of fiber anatomical cross-dimensions, it can give a general idea of the average cell wall proportion in pulp fibers, though. In this study, the average coarseness values for whole pulps, as well as for their long fiber (Bauer-McNett R14 and 14/28 mesh) fractions were determined with the Kajaani FS-200 Fiber Analyzer from pulp samples. A complete description of the Kajaani method and its uses in TMP evaluation, can be found in Kajaani Fiber Analyzer (1986) and Paavilainen (1993).

The average *width (or diameter) of fibers* and *cell wall thickness* of for the long fibers (Bauer-McNett R14 and 14/28 mesh fractions) of SM, OG, and FT end-use pulps were determined. The method of analysis and used technique has already been described in Section 3.3.2.2. This same image analysis technique was employed in determining the earlywood/latewood ratio (or *latewood content*) in the long fiber fractions of end-use pulps. It should be noted that in the case of pulps, the latewood content refers to the number of latewood fibers, expressed as percentage and defined as by Mork (1928b). Thus the obtained values are not necessarily comparable to those determined from wood, basing on different technique (Section 3.3.2.2).

Perhaps the most commonly used method to characterize mechanical pulp and its particle composition is Bauer-McNett fiber classification (or fractionating). This method was also used here, its utilization in evaluating mechanical pulps being described in numerous studies and pulping textbooks (see e.g. Forgacs 1963, Mohlin 1979, Shalhorn & Karnis 1979, d'A Clark 1985, Leask 1987). A thorough description of the methodology using Bauer-McNett is found for instance in reference Butler (1948) and Tappi Standard T233.

Useful information of mechanical pulp fiber properties can be obtained also with a Sunds Defibrator Pulp Quality Monitor (PQM), which has, in fact, recently become a customary equipment in Scandinavian mechanical pulping industry. In this investigation, it was also employed to determine the fiber and particle properties in pulps. Actually, it is a laboratory classifier that incorporates a linear camera with integrated parallel image processing to determine the shive and particle size distribution. The derived data using this methodology includes the average fiber length and the distribution of fibers into long, middle and fine fiber particles and is obtained by measuring light intensity variations originating from light scattering and absorption in a suspension. The required sample size per one test is about 3 grams pulp, calculated in oven-dry basis. Furthermore, the PQM shive data consists of the total number of shives ("sum shives"), and the number of shives that are classified either as wide, long or coarse shives. The number of shives particles are categorized in a two dimensional matrix, according to their width and length. The width classes are: < 0.075 mm, 0.075 < 0.150 mm, 0.150 < 0.300 mm, 0.300 < 0.600 mm, and > 0.600 mm, and corresponding length classes: < 1.5 mm, 3.0 < 6.0 mm, and > 6.0 mm, respectively. More information of this methodology can be found in Rydefalk et al. (1981).

The papermaking properties of different mechanical pulps have been shown to differ in ways that cannot always be adequately explained using conventional pulp testing methods, such as the Bauer McNett fractions (Laamanen 1983, Mohlin 1979). Belonging to this cagegory, the *fibrillation index* was determined using the method, developed at FPPRI, for the long fiber fractions (Bauer McNett +14 and 14/28) of end-use pulps, made from different type of wood Laamanen 1983). This morphological characteristics of fibers is defined as the proportion of fiber surface, showing external fibrillation, to the length of fibers, and it is a measure of external fibrillation resulting during the fiber development in a refiner. Abundant fibrillation in mechacinal pulps contribute to sheet strength and printing properties. As in the case of other fiber morphological properties, light microscopy and image-analysis technique were applied for measurements on fibers, which were first placed on glass plate (see Section 3.3.2.2). The same technique for the determination of fibrillation index, has been earlier used by Laamanen (1983) and Ora (1987).

Designed especially for finer particles, other methods used in evaluating the paper making potential of mechanical pulps are *specific filtration resistance* and *specific sedimentation volume*. Those methods were also used here. The former, expressed as m/kg^2, characterizes the specific surface in mechanical pulps, and thus the bonding ability, of fiber fractions. It was obtained by determining the pressure difference during the filtration of fiber suspension and this method is suitable especially for evaluation of short fibers. *Specific sedimentation volume* is defined as the volume of turbid section of a slurry of pulp fines fraction, when being sedimentated for 24 hours, divided by its oven-dry weight. The higher the obtained numerical value, the better the bonding ability of a pulp. More information on how the determination was carried out in this study, is found in reference Heikkurinen (1992).

Supporting the understanding of the above mentioned quantitative pulp properties evaluations, qualitative data, although admittedly subjective, can be obtained from mechanical pulp fiber material with microscopy, as has been done already by the early mechanical pulp investigators, such as Forgacs (1963), Koran (1966) etc. The above methodology can reveal not only fundamental differencies between particles originating from different pulping processes – TMP, SGW, CTMP, kraft, etc. – but valuable information could be obtained from the development of important quality properties within a pulp or its separate fraction during pulp processing. Furthermore, sheet consolidation is often evaluated with microscopy. However, great caution should be followed in interpretation due to the nature of data and sample size, being usually only a small number of fibers. In this study, the qualitative analysis was carried out to long fiber fractions (BaurMcNett 14/28) of the trial pulps, in the form of optical and scanning electron (SEM) microscopy. Small representative samples of the long fiber fractions of all pulps – 1-stage and 2-stage pulps (Line A) as well as end-use pulps (Lines A–C) – were collected for detailed microscopical analysis using both the light microscope and the scanning electron microscope. Special care was taken in order to obtain representative micrographs of the samples studies.

The pulp samples used for scanning electron microscopy were dehydrated by solvent exchange with tertiary butanol and subsequently freeze-dried. This two-stage drying technique ensured thorough removal of moisture without any detrimental effect on the fiber structure. The samples were coated with gold for improved electron beam and high secondary electron yield. Electron micrographs were taken with 500× magnification. The apparent angle of viewing was 45 degrees to the plane of the sample. For photomicrographs, the samples were stained with an aqueous solution of Chlorazol Black E (Forgags 1963). This solution stains both cellulose and lignin. The stained samples were air-dried and mounted on glass plates. They were then examined in a Axioplan microscope. The configuration has been described earlier, in Section 3.3.2.2. The used magnifications were 50 and 200 times.

3.3.5 Statistical Analysis

As already mentioned earlier, all tests and determination of individual wood and pulp properties, were made according to Scandinavian (SCAN) standards, if such existed. If this was not the case, attemption was made to apply other standard or previously-used methods. Thus, the testing and measuring methods themselves provided satisfactory repeatability and realiability in obtaining an estimate from an individual property. When determining wood or pulp properties in this study, a sufficent number of samples, i.e., degrees of freedom, were provided to obtain average values with enough statistical significance.

Although, there were several independent (wood properties) and dependent (pulp properties) variables, the design of this mill-scale experiment did not allow the use of statistical analysis methods based on multivariate statistical analysis, such as multiple regression. Namely, such analysis require always a sufficent number of observation points where values for both independent and dependent variables exist. In this study, although being relatively representative of the materials used in trials, there are actually only few true observation points per independent or dependent variable. This is due to the fact that one trial pulp or "TMP batch" – obtained from SM, RC or FT wood raw materials – consists of the whole 24 hour production period. With respect to the variation that exists in both wood raw material and pulp properties, chip samples for the wood properties determination and a subsequent pulp samples (with its properties) refined exactly from these chips is rather impossible to provide (see e.g. Cort et al. 1992, Strand et al. 1993, Hill et al. 1993). For the same reason, the principal component analysis, meta-analysis, and time series analysis, which all methods otherwise offer valuable statistical tools, were disabled (see e.g. Hedges and Olkin 1985, Joliffen 1986, Ranta et al. 1989).

However, an analysis of variance was performed to determine the statistical significance of differences in mean values of examined individual wood and pulp properties between the three raw material sources. This method facilitates comparisons with the mean values of individual properties between each raw-material (SM, RC, and FT woods) or pulp (SM, RC, and FT pulps) populations (see Mendenhall 1968, Ranta et al. 1989). Throughout the study, 1 % level of significance was used to test if deviation in average wood, as well as pulp properties was statistically significant. The expected differencies, if such existed, in the properties of obtained thermomechanical pulps, could be then explained with variation in wood properties. However, a statistically significant difference in some wood or pulp property is not necessarily significant in practice. Interpretation of such results must always be done together with experts from the relevant area of substance. As earlier discussed, the idea of this mill scale refining trial was to provide constant process conditions. The expected influences of Norway spruce wood properties to TMP quality and manufacture, were established in the teoretical part of the study (Chapter 2), derived from literature that bases mainly on laboratory-scale studies.

As being clear from the above, the refined wood chips from each raw material type formed statistically a population and using different sampling techniques, data from those populations, in the form of average properties and their variation, could be established. A comment should be made here, concerning the interpretation of results of the analysis. It is known that as a representative sample always contains the relevant characteristics of the population in the same proportion as they are included in that population (Levin 1978, Ranta et al. 1989), it is just an impossible task to determine the properties of whole populations in practice. Thus, the results are representative of only these raw materials and pulps made out of them. However, with reservations, these wood raw materials (forest stands, residual chips) could be thought as samples representing common conditions for Finnish or Nordic spruce, and the derived pulps representing typical newsgrade thermomechanical pulps from the above areas, comparatively.

3.4 Results

3.4.1 *Important Wood and Fiber Properties and Their Variation in Raw Material – Forest Stands and TMP Chips*

Average wood *basic densities* in each of the three different wood assortments – saw-mill residual chips, regeneration cut wood and first-thinnings wood – were 383 kg/m³, 425 kg/m³ and 396 kg/m³, the corresponding sample standard deviations being 22 kg/m³, 37 kg/m³, and 26 kg/m³, respectively. The differences between all three wood types are statistically significant. The results are presented in the following chart (Fig. 44), and also along with other wood properties, in Table 23.

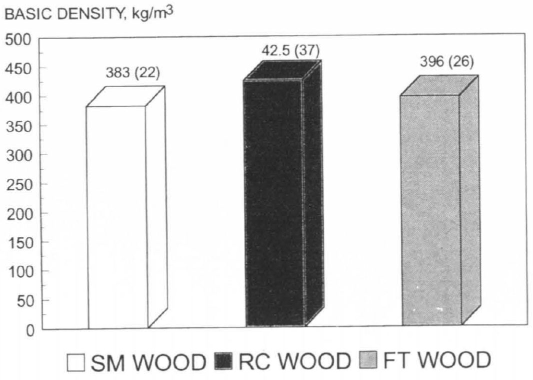


Figure 44. The obtained average basic densities in saw mill chips (SM), regeneration cuttings wood (RC) and first-thinnings wood (FT). Standard deviation shown in brackets.

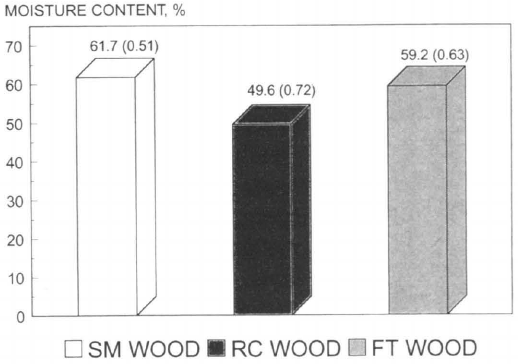


Figure 45. The obtained average moisture content in saw mill chips (SM), regeneration cuttings wood (RC) and first-thinnings wood (FT). Standard deviation shown in brackets.

The obtained values can be considered being well in accordance of previous findings, and therefore as typical for southern Finland (see Section 2.2.1). Hakkila reports the average spruce pulpwood basic density of 382 kg/m³ at latitudes between 62nd and 64th parallel. Values similar to the results of this investigation have been reported as well from other parts of Scandinavia at similar latitudes and elevations, namely in Central Norway (Okstad 1988) and Sweden (Tamminen 1964).

The obtained average values for wood *moisture content*, in wet-basis (MC_w), were 61.7 (s.d. 0.51) for SM-chips, 49.6 (s.d. 0.72) for RC-chips and 59.2 % (s.d. 0.63) for FT-chips. This is shown in Figure 45 (see also Table 23 and Appendices 1–2). The differences between each wood raw-material were statistically significant and reflected well the deviation that typically occur between these wood types (see Section 2.3.1). Moreover, the relatively high moisture content values, even RC chips, can be considered as normal in terms of seasonal variation and delivery of the trials wood to the mill. According to Okstad (1988), the average wood moisture content in Norway spruce trees grown in Scandinavia increases by about 30 %, from 38 to 51 %, during the period July-December.

Table 23. Wood and fiber properties in Norway spruce sawmill residual wood, old-growth wood and first-thinnings wood, used in TMP manufacture.

Property	Wood type Sawmill residuals	 Regeneration cuttings	 First-thinnings
Basic density, kg/m³	383	425	396
Moisture content, %	61.7	49.6	59.2
Fiber length, mm	3.02	2.39	1.91
Fiber diameter, µm	39.8	31.8	22.7
Lumen size, µm	32.6	25.4	19.3
Cell wall thickness, µm	3.7	3.3	1.8
Fiber coarseness, mg/m	0.303	0.243	0.140
Latewood content, %	19.7	23.1	21.5
Juvenile wood content, %	0	16.9	58.3
Heartwood content, %	0	43.0	15.3
Extractives content			
DCM, %	1.04	1.03	1.33
Ethanol, %	0.31	0.44	0.77
Total, %	1.35	1.47	2.10

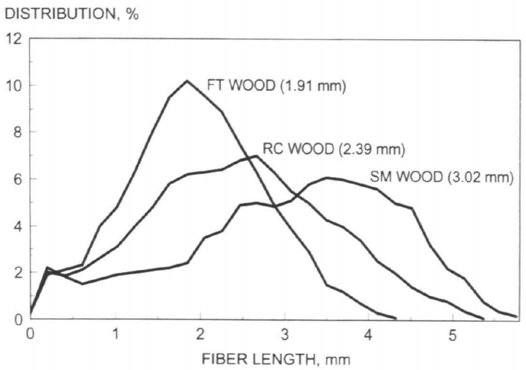


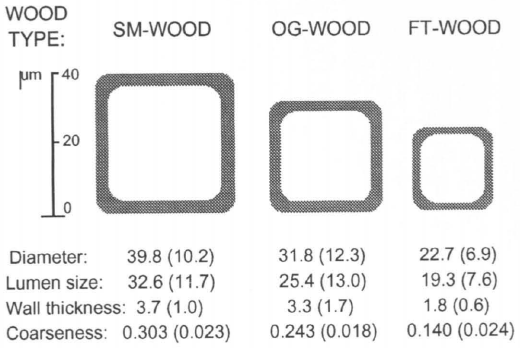
Figure 46. Length-weighted average fiber length distributions in the three different spruce raw materials used in TMP manufacture. Average wood fiber length is shown in brackets. SM = saw mill residual wood, RC = regeneration cuttings, FT = first-thinnings wood.

Average *fiber length*, expressed as length-weighted length, in all three different woods was 3.02 mm for sawmill residual wood (SM), 2.39 mm for old-growth wood (OG), and 1.91 mm for the first-thinnings wood (FT). Standard deviations of the average fiber length between samples were, 0.24, 0.36, and 0.18 mm, in the same order. Also weight-weighted average fiber lengths were obtained. Using this computation (Kajaani-method), the corresponding values were 3.61, 2.91 and 2.28 mm. In the calculated weight-weighted fiber length, the coarseness of the fibers is assumed to be proportional to their length, which is not necessarily true. However, average fiber length values for these three wood types, expressed in both ways, are well in accordance what is known of fiber length variation in softwoods and especially in Norway spruce (see Section 2.4.1). The length-weighted average fiber length is presented in Table 23.

Figure 46 presents the average fiber length distributions obtained from each wood. As could have been expected, the wood from first-thinnings stands had the narrowest distribution, thus including mostly relatively short (or juvenile) tracheids. On the other hand, wood from old-growth forests (RC) had the "widest" distribution, including a large variety of fiber lengths. Saw mill residuals, that is, chips from the sapwood part of the log, consisted of mostly long, mature fibers.

Note the subtle peak on the low end of the fiber length curves, which is mostly due to the presence of parenchyma cells in wood or broken tracheids. Since the fiber lengths were obtained from chipped wood, including both the whole tracheids and cut tracheids resulting from chipping operation, the values are somewhat shorter than the true tracheid lengths based on roundwood.

Values for the average fiber cross-sectional dimensions, i.e. *fiber diameter, fiber wall-thickness, lumen size*, in the wood raw-materials used in this study are shown in the following figure (Fig. 47) and in Table 23. As could have been expected, significant differencies existed between the average values. The obtained values for average fiber diameter and wall thickness are rather somewhat higher than reported in theoretical part of the study



All units in micrometers except coarseness in mg/m

Figure 47. A schematic drawing of relative average cross-sectional tracheid dimensions in saw-mill chips (SM), regeneration cuttings wood (RC) and first-thinnings wood (FT), based on microscopical analysis. Numbers in brackets indicate the standard deviation between samples.

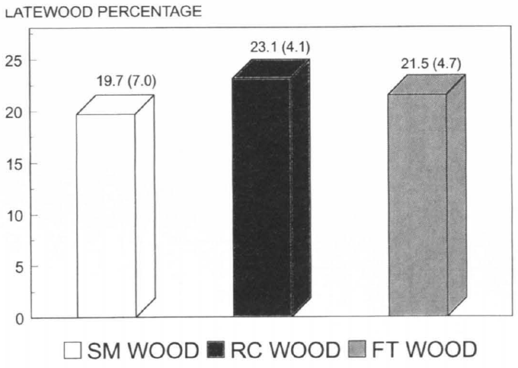


Figure 48. Average latewood content in three different spruce wood raw-materials, expressed as volume percentage in total wood volume (w/o bark). SM = saw mill residual wood, RC = regeneration cuttings stands, FT = first-thinnings stands.

(see Section 2.4.1). Sawmill chips had fibers with the largest diameter and thickest walls. On the contrary, first-thinnings wood was comprised of tracheids that had the thinnest cell walls and smallest width. The properties of the wood from regeneration cutting fall between these two extremes.

The average *tracheid coarseness*, i.e. the mass per unit length of fibers, is shown in Table 23. This property, mostly used to evaluate chemical pulp fibers, can give useful information of the pulp and paper making potential of a given wood. The obtained values for SM, RC and FT woods were 0.303 mg/m (0.023), 0.243 mg/m (0.018) and 0.140 mg/m (0.024), respectively. The numbers in brackets show the sample standard deviation. Another fiber parameter that has often been used to evaluate the pulpwood species is *fiber flexibility coefficent*. Actually, it is a theoretical value derived from the ratio of lumen width to fiber diameter. Obtained values of this parameter were 0.82 for SM wood, 0.80 for RC wood and 0.85 for FT wood, suggesting that there should be no big differences in theoretical flexibility of fibers.

Latewood content in sawmill residual wood, expressed as a volume-based percentage, was 19.7 % (s.d. 7.0). Corresponding values for regeneration cuttings and first-thinnings woods were 23.1 (s.d. 4.1) and 21.5 % (s.d. 4.7). These average values have been obtained by weighing with the roundwood volume delivered from each stand, in order to get a reliable estimate of the incidence of latewood in TMP chips. Numbers in brackets show the sample standard deviation between sample trees from RC and FT stands and chips from SM wood. These results can be seen in Figure 48 as well as in Table 23, together with other wood properties. Similar values for average latewood content at the comparable geographical latitudes have been obtained for Norway spruce by other investigators as well (see Section 2.6.1). Namely, according to Hakkila's (1968) extensive study, the average latewood content in spruce pulpwood varied from 18 to 27 %, within a hypothetical circle of which midpoint is Varkaus and radius approximately 50 km.

Figure 49 and Table 23 show the average *content of juvenile wood* in the trial wood raw-materials. In RC wood, the average content of juvenile wood was 16.9 (s.d. 4.4), and in FT wood 58.3 % (s.d. 8.3). In these two woods, the content of juvenile wood was determined from sample stems collected from different forest stands and expressed as its actual volume percentage in the stem (w/o bark). The average juvenile wood percentage for RC and FT woods is computed by weighing the stand averages by derived roundwood volume from each stand. However, the values in parentheses show the standard deviation between

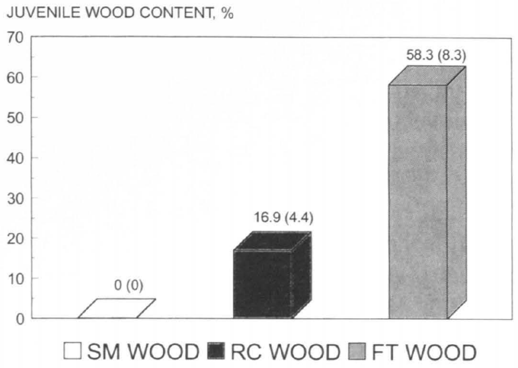


Figure 49. Average juvenile wood content in three different spruce wood raw-materials, expressed as volume percentage in total wood volume (w/o bark). SM = saw mill residual wood, RC = regeneration cuttings stands, FT = first-thinnings stands. Standard deviation is given in brackets.

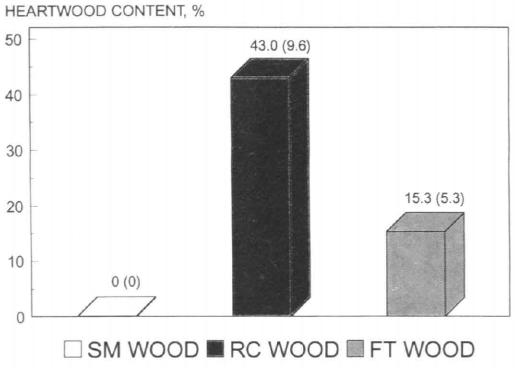


Figure 50. Average heartwood content in three different spruce wood raw-materials, expressed as volume percentage in total wood volume (w/o bark). SM = saw mill residual wood, RC = regeneration cuttings stands, FT = first-thinnings stands. Standard deviation between the samples is given in brackets.

all sample stems. Elsewhere in Scandinavia, values from as low as 10 %, for old trees, to as high as 80 %, for 20 year-old trees have been reported for Norway spruce (Boutelje 1968). The average age were the formation of juvenile wood had ceased, or actually leveled off, as determined here from the tracheid elongation, was 24 years in old-growth stands (RC) and 26 years in first-thinnings stands. In saw mill residual wood (SM), the juvenile wood content is assumed to be 0 %, since only the outermost parts of saw logs were chipped for TMP raw materials. To assure this, the residual wood chips made of wood pieces from the trimming saws, as the boards and blanks are cut-to-length after kilning, were strictly excluded from the trial, being sent to the company kraft pulping mill.

Like in the case of juvenile wood, the *content of heartwood* is assumed to be practically 0 % in SM wood, since it was not allowed in chips. For RC wood, the average heartwood content was 43,0 % (s.d. 9.6), and for FT wood, as low as 15,3 % (s.d. 5.3). These values are calculated from the average forest stand data derived from sample trees. Moreover, in order to obtain an estimate of heartwood in the TMP chip flow, they were weighted with the procured wood volumes from each stand. Values are expressed as actual volume of heartwood from the total wood volume (w/o bark), and numbers in parentheses show the standard deviation between all sample stems.

Heartwood content in the wood material is shown in Figure 50. Now obtained heartwood contents in different wood assortments seem to be well in accordance with earlier investigators (see Section 2.8). For various Norway spruce pulpwood assortments, Bruun (1967) has obtained average values varying from 19.1 to 29.1 % (volume), in comparable geographical localities in Finland. These average values are for whole stems. Nylinder and Hägglund (1954), in their massive study performed in Sweden, found the Norway spruce stems, at 25 % relative tree height, to have 45.3 % (s.d. 18.6) heartwood in an average. Moreover, when the average ring-width decreased from 2 to 1 mm, the average heartwood percentage increased up to 70 %.

The total *extractives content*, including the dichloromethane- (DCM) and ethanol-soluble compounds, was lowest, i.e. 1.35 % (s.d. 0.19) in SM wood, 1.47 % (s.d. 0.31) in RC wood, and highest in FT wood, being 1.77 (s.d. 0.25). The breakdown of the total extractives content to DCM and ethanol extracts is shown in Figure 51. and also in Table 23. Similar values have been obtained in Finland and other parts in Scandinavia,

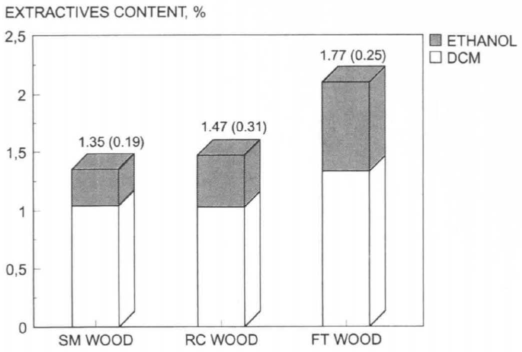


Figure 51. Average extractives content in three different spruce wood raw-materials, expressed as weight percentage from wood (w/o bark). SM = saw mill residual wood, RC = regeneration cuttings stands, FT = first-thinnings stands.

comparable with the geographical location of Varkaus, for sprucewood average extractives content (Brolin and Noren 1993). The total quantity of extractives of spruce pulpwood is known to increase by almost 100 % toward the north. Irrespective to their chemical composition, no big difference in total extractives content in Norway spruce sapwood and heartwood. Topwood usually have 20 % higher content of extractives than other stem parts (see Section 2.10.1).

It should be noted that the wood seasoning could not have had any major influence on the extractives content of wood, firstly due to extremely short time – only a few days – from stump to pulping process, and secondly because of Nordic winter conditions (Nugent et al. 1977, Pennanen et al. 1993).

3.4.2 Pulp Properties

Mechanical pulps are often manufactured to and compared at a given *freeness* value, which is said to simulate the pulp's water removal ability on a paper machine. However, the higher is the paper machine speed, like in present day modern machines, the lower is the accuracy of this laboratory measurement to predict the pulp's real water removal capability (Paulapuro and Laamanen 1988). Besides this, freeness measurement is very sensitive to pulp specific surface and particle distribution. It is true that many pulp properties are highly correlated with freeness. This is especially so in groundwood, and can be also a valid argument in other mechanical pulps, if production conditions, such as refiner plate wear or wood raw material quality remain quite constant (see e.g. Michelic 1972, Kurdin 1979, Leask 1987a). Since pulp production should focus on consistent quality in the sense of sheet properties, rather than producing a pulp of specified freeness, it can be confusing to compare properties of pulps from fibers with such extremely different characteristics as juvenile wood and mature wood at a constant freeness. Therefore, it was considered to be more important to compare the properties of SM, RC, and FT pulps at a constant energy consumption level, rather than at constant freeness. However, comparisons were made also at constant freeness.

3.4.2.1 Pulp Energy Consumption

In this study, calculation of the TMP *specific energy consumption* (SEC), that is, the consumed energy to manufacture a ton of oven-dry pulp at a specific freeness, included all main refiner lines – lines A, B, and C – and rejects refiners. In addition to end-use pulps, SEC values were determined for the first- and second-stage refiners of the refining line A. The obtained values are average values for the whole refining trial period, which was actually one day (24 h) per each raw material. Due to relatively homogenous wood raw material and controlled production conditions during the trials, very little deviation occurred in pulp power consumption. The following figure (Fig. 52) shows the specific energy consumption as a function of freeness for the obtained pulps.

There were no significant differences in the power consumption of end-use pulps made from different type of wood raw materials, when compared at a given freeness level. *Thus, hypothesis 1 is well supported* (see 2.11.3.). When energy consumption is plotted with some other pulp properties, such as strength or optical properties, the situation is totally different. This is shown in later sections. To produce newsgrade TMP according to EG-Varkaus specifications, i.e., to CSF 75 ml freeness level, all pulps consumed approximately 2 MWh/t energy. This is typical, or somewhat lower what is usually reported for Norway spruce in mill-scale production (Nyblom 1979, Härkönen et al. 1988) Actually, it was not possible to refine all pulps to this specification, because it would have affected to pulp strength or other production controlled properties. This indicates clearly, that freeness value is not the best production control parameter or indicator if different raw materials are used in TMP manufacture, or standard production conditions should not be used for all of these woods. When the specific energy consumption values of pulps, passed the primary and secondary refining, were interpolated to constant CSF 120 ml freeness level (Appendix 7), pulp from sawmill chips (SM) consumed averagely 1780 kWh/t, pulp from regeneration cuttings (RC) 1772 kWh/t and that from first thinnings (FT) 1765 kWh/t. These differences are neither very dramatical and nor statistically significant.

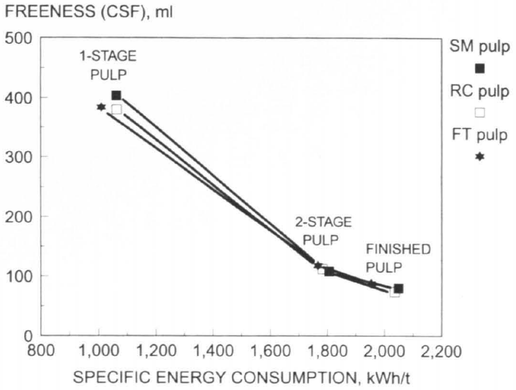


Figure 52. The spesific energy consumption (SEC) as a function of freeness of Norway spruce thermomechanical pulps made from saw mill chips (SM), regeneration cuttings (RC) and first-thinnings (FT).

3.4.2.2 Pulp Fiber and Particle Properties

TMP fiber and particle properties, referred here in broad sense, mean those morphological and structural properties of pulp fiber and fines material, that are usually expected to have influence on the behavior of fiber network in paper making process. Properties of mechanical pulps are often compared using the Bauer-McNett fiber classification, since the proportions of different fractions have their influence on pulp's paper making potential. Generally, the long fiber (R28 or R48) and the fines fractions (P200) are the two most important fractions influencing the strength of TMP (Mannström 1972, Mohlin 1979, Corson 1980). Karnis (1993), for instance, divides the final constituents of a papermaking mechanical pulps into the following four categories:

1. Fiber bundles i.e. shives and minishives.
2. Long fibers: fibers retained on the 48 mesh screen of a Bauer-McNett classifier; their length is greater than 1.44 mm.
3. Short fibers: Fibers passing the 48 mesh screen but retained on 200 mesh screen; their length lies between 0.52 and 1.44 mm.
4. Fines: Material passing the 200 mesh screen with length less than 0.52 mm.

The optimum pulp strength, especially the tear strength, will be achieved when the pulp contains a maximum of well-developed long fiber and a minimum of shortened fiber. However, such pulp should have a sufficient amount of fine material available to consolidate it into a dense network with good wet web and dry sheet properties. This is because, in contrast to chemical pulp fibers, mechanical pulp long fibers are several times stiffer, which leads to a fact that there are much more less bonding surface (Mannström 1968, Jackson and Williams 1979). Therefore, the fines particles between the network forming fibers, are of the greatest importance.

Good mechanical pulp optical properties can be mainly attributed to a large proportion of fines fraction due to its high specific surface. It should be noted that not only the quantity, expressed as percentage of particles retained on different screens of the Bauer-McNett apparatus, but the quality of these fractions largely affect mechanical pulp properties. In fact, the quantity and quality of different TMP fractions are independent from each other, and can be influenced separately in refining (Mohlin 1979, Kurdin 1979). The relative flexibility of pulp fiber material and good bonding properties of all fractions contribute pulp quality to a great extent. These properties depend partly on the type of wood raw material used, but can be further enhanced by refining. Expected influences of intrinsic fiber properties, such as fiber length and fiber dimensions, on TMP properties, were already discussed thoroughly in theoretical part of this investigation (Chapter 2).

BauerMcNett Fiber Fractions and Pulp Shives Content

The proportions of different fractions, classified with the Bauer-McNett fiber fractionator, are shown in the following figure (Fig. 53) for the end-use pulps made from different wood raw-materials. The development of these fractions through the first- and second-stage refiners in the control-line A, and finally to end-use pulps can be also seen in Appendices 4–6. As could have been expected, the content of long fibers (R28) decreased and content of fines material (P200) increased in all pulps along with refining energy input.

As mentioned before, it is well justified to discuss of the share of different particle fractions in the final freeness values ("as is"), since it represented real TMP furnish which were pumped onto a paper machine. The obtained proportions of different fractions can be considered as typical for newsgrade TMP made from Norway spruce (Paulapuro et al. 1983, Härkönen et al. 1988, Högglund and Wilhelmsson 1993), however, significant differencies occurred between pulps made from different type of raw-material. The *long fiber fraction* retained on the Bauer-McNett 28 mesh sieve was highest for pulp made from sawmill chips (SM), and lowest for first-thinnings (FT) pulp. SM pulp had 36 % more, and RC pulp 27 % more long fiber than FT pulp. The obtained results are well in accordance both with the wood and pulp average fiber lengths, as well as with other obtained fiber properties, discussed later.

TMP *fines material* is shown to be comprised of ray tracheids, ray parenchyma cells, flake-like fragments from middle lamella and bandshaped fragments from secondary wall (Gierz 1977, Heikkurinen 1992). Furthermore, the nature of these fragments, that is, their relative proportions and ultrastructure, is shown to change according to applied energy during refining. Formation of fines particles is largely dependent on the process conditions, and only to a lesser degree on the wood raw-material properties. Like in the case of long fibers (R28), the most commonly used method for characterization of fines has been to measure the weight percentage of particles passing through the 200 mesh screen of a Bauer-McNett classifier. However, this method is not sensitive enough to detect the surface area variations of fines, because fines have a large surface compared to their mass. A better understanding can be often obtained using other characterization methods, such as *specific filtration resistance*, also used in this study.

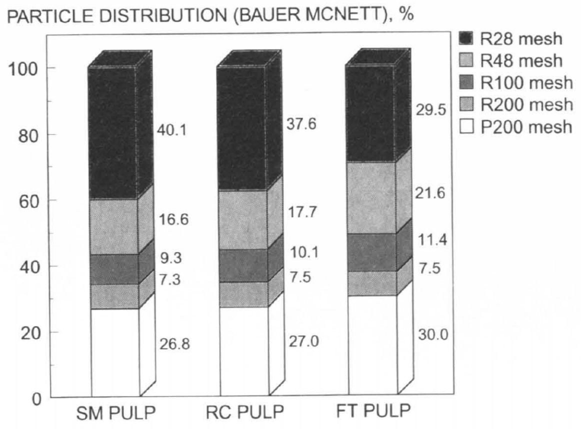


Figure 53. Particle distributions of end-use thermomechanical pulps made from Norway spruce sawmill chips (SM), regeneration cuttings (RC), and first-thinnings (FT). Final average freeness (CSF) values for these pulps were 80, 74, and 88 ml, in the same order, the applied energy being constant (2.0 MWh/t) for all pulps.

At constant SEC level of 2MWh/t, the share of fines was highest in FT pulp and lowest in SM pulp. FT pulp had 12 % more fines particles by weight than SM pulp and 11 % more than RC pulp. *It can be stated that the proportions of fractions are well in accordance with the hypotheses 2–4* (see Section 2.11.3.). The relative proportions of these fractions do not change dramatically, if pulps are examined at constant freeness level, in the range of typical newsgrade pulp. The relative proportions of both long-fiber and fines fractions were confirmed by the results from PQM-analysis, shown in Appendix 8. Generally in thermomechanical pulping, as the proportion of long fibers decreases and that of fines material increases along with decreasing freeness, the share of middle fractions (R48/200) does not change so much (Jackson and Williams 1979, Lindholm 1981a,b).

Table 24. Properties of newsgrade end-use thermomechanical pulps manufactured from different spruce wood assortments.

Pulp property		Pulp type	
	TMP from sawmill chips	TMP from regeneration cuttings	TMP from first-thinnings
Pulp energy consumption, MWh/t	2.0	2.0	2.0
CSF Freeness, ml	80	74	88
Consistency (discharge), %	10.5	9.4	10.0
Fiber and particle properties			
Average fiber length, mm	1.72	1.63	1.32
Bauer McNett-fractions:			
+28 mesh, %	40.1	37.6	29.5
+48 mesh, %	16.6	17.7	21.6
+100 mesh, %	9.3	10.1	11.4
+200 mesh, %	7.3	7.5	7.5
–200 mesh, %	26.8	27.0	30.0
Shives cont. (Somerville), %	0.14	0.21	0.10
Shives number (PQM), no/g	1272	1407	1138
Fiber coarseness (14/28 mesh), mg/m	0.341	0.278	0.221
Fiber diam. (+14 mesh), µm	34.1	29.4	24.3
Fiber wall thickness (+14 mesh), µm	3.1	2.6	2.0
Latewood fibers by w. (+14 mesh)	23.6	20.9	10.1
Latewood fibers by w. (14/28 mesh)	14.3	12.9	5.9
Fibrillation index, %	60	44	44
Specific filtration resistance (48/200 mesh), m/kg	236	313	152
Specific sedimentation volume (–200 mesh), dm^3/kg	513	526	501
Sheet properties:			
Sheet apparent density, kg/m^3	414	412	405
Bulk, m^3/kg	1.89	1.82	1.87
Air resist. (Bendtsen), ml/min	120	130	170
Roughness (Bendtsen), ml/min	270	230	260
Mechanical properties:			
Tear index, mN·m^2/g	8.60	8.39	7.65
Burst index, kPa·m^2/g	3.09	3.18	2.80
Tensile index, N·m/g	45.9	47.2	40.8
Tensile stretch, %	3.1	3.8	3.4
Optical properties:			
ISO Brightness, %	58.2	59.6	61.7
Light scattering coeff., m^2/kg	54.1	56.4	61.4
Light absorption coeff., m^2/kg	2.99	2.87	3.21
Opacity, %	95.8	95.7	96.1
Other pulp properties:			
Extractives content (DCM), %	0.83	0.57	0.43

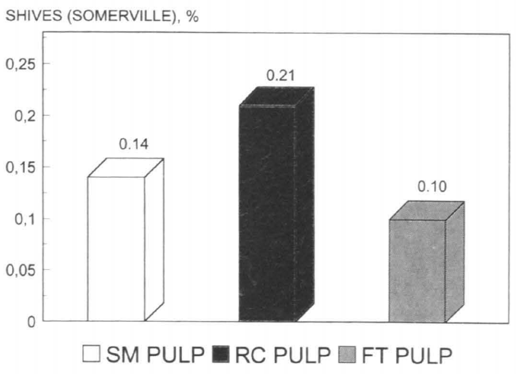


Figure 54. Average shives (Somerville) content in newsgrade end-use thermomechanical pulps, made from Norway spruce sawmill chips (SM), regeneration cuttings (RC), and first-thinnings (FT). Final average freeness (CSF)values for these pulps were 80, 74, and 88 ml, in the same order, the applied energy being constant (2.0 MWh/t) for all pulps.

This was the case also in this study, shown in Appendices 4–7.

Shives, that is, the unfiberized debris particles, are an inevitable product of the mechanical pulping process. Their proportion in the pulp will depend on the physical characteristics of the wood raw material and the type and intensity of the pulping process involved. Low shives content is very critical in the production of newsprint, since they can cause severe runnability problems in paper and printing machines. The content of shives in newsgrade end-use pulps, made from different wood raw-materials is shown in Figure 54 and Table 24. The Old-growth wood (RC) yielded the highest proportion of shives, having 50 % more than pulp from sawmill chips, and over twice as much shives by weight than the first-thinnings pulp. *The above is well in line with the hypothesis 3* (see Section 2.11.3). Somerville-shives content cannot be considered relatively high for any of those pulps (Lindholm 1984, Paulapuro and Laamanen 1988, Haikkala et al. 1990).

Corresponding average values for the *shives number*, in terms of PQM-analysator test results, were 1272 for SM pulp, 1407 for RC pulp and 1138 for FT pulp. Here, the order between different pulps is identical with the above case of shives weight proportion. The high value of OG pulp

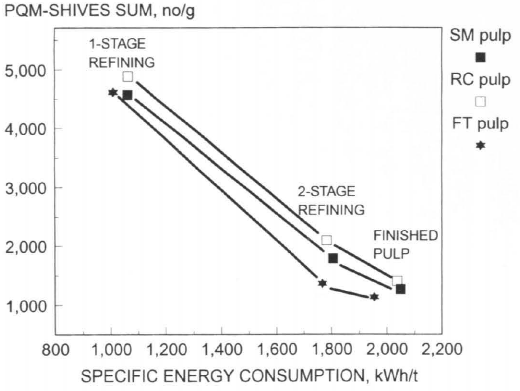


Figure 55. The development of shives (PQM) sum number according to TMP spesific energy consumption. SM = saw mill chips, RC = regeneration cuttings, FT = first-thinnings wood.

falls close to the minimum company quality specification of 1500 particles in a gram of pulp. The reduction in shives number according to applied energy is shown in the Figure 55 for all pulps. The shive classification according to their size and form did not show any dramatical differencies between the pulps (see Appendix 8).

Fiber Length

TMP made from sawmill chips had the highest average fiber length, being 1.72 mm, while that for pulp originated from the first-thinnings wood was the lowest, 1.32 mm. Corresponding value for newsgrade TMP made from old-growth regeneration cuttings wood was 1.63 mm. Regardless of considerable differences found in average fiber lengths between pulps, these values can be considered though as typical for Norway spruce TMPs refined to below 100 ml freeness (CSF) level (see e.g. Lindström et al. 1977, Härkönen et al. 1988, Paulapuro and Laamanen 1988). The reduction of length-weighted average pulp fiber length according to applied energy is shown in Figure 56. Data on average fiber properties can also be seen from Table 24, shown earlier. With respect to average fiber length and its distribution found in original wood raw-materials (Fig. 45), those for obtained pulps fell into the same relative order.

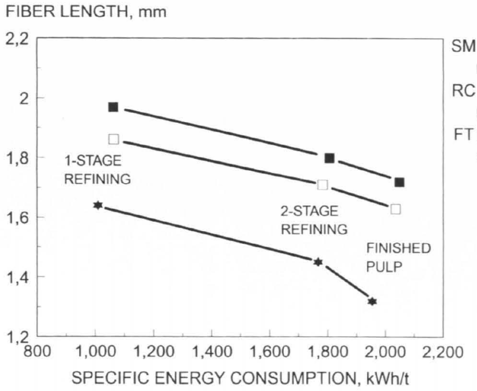


Figure 56. Reduction in length-weighted average fiber length according to applied refining energy in thermomechanical pulps made from different wood raw-materials. SM = sawmill chips, RC = regeneration cuttings, and FT = first-thinnings wood.

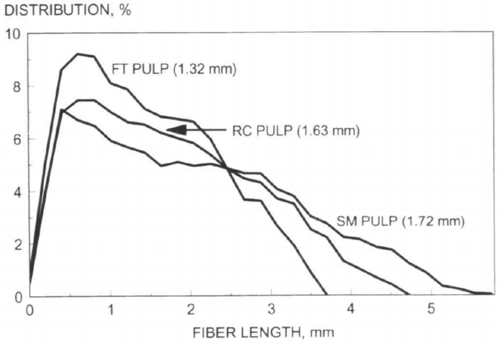


Figure 57. Average fiber length distributions of newsgrade end-use pulps made from saw mill chips (SM pulp), old-growth regeration cuttings (RC pulp), and first-thinnings (FT pulp). Values are obtained with Kajaani-FS200 apparatus and are expressed as length-weighted averages. Pulp average fiber length shown in brackets.

The distribution of fiber length in newsgrade end-use pulps is shown in Fig. 57. When compared at 2.0 MWh/t SEC level, the differences in the fiber distributions SM, RC and FT pulps reflected well the differences in their Bauer-McNett fiber classification and mean, length weighted average fiber lengths. Although the proportion of long-fibers by weight, i.e. percentage of Bauer-McNett R28 fraction, was only slightly higher in SM compared to OG pulp (Fig. 53), the average length of those fibers, however, is considerably higher in SM. This can be easily observed from the form of the SM pulp curve in Figure 57. The average fiber length in the long fiber fraction (R14/28) was also highest in SM pulps. Compared at 100 ml freeness (CSF) level, the average fiber lengths of SM, OG and FT pulp long fiber fractions were 2.41 mm, 2.07 ans 2.0 mm, respectively. Furthermore, as shown in Appendices 4 to 7, when the long fiber fractions of each pulp were examined separately, it was found that the average fiber length within this particular fiber fraction from A1- to A2-pulps, and finally to end-use pulps did not decrease dramatically, at least if compared with that of whole pulps (Fig. 57). *As a whole, obtained results in terms of pulp fiber length factors are well in accordance with hypotheses 2–4* (see Section 2.11.3).

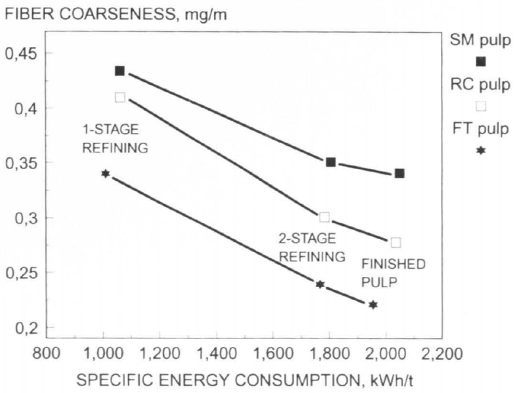
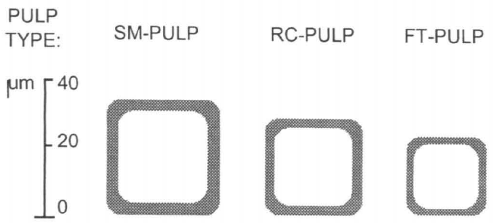


Figure 58. The fiber coarseness in long fiber fractions as a function of pulp specific energy consumption (Bauer-McNett R14 mesh) of thermomechanical pulps made from sawmill residuals (SM), regeneration cuttings (RC) and first-thinnings wood (FT).



	SM-PULP	RC-PULP	FT-PULP
Diameter:	34.1 (6.7)	29.4 (8.9)	24.3 (4.3)
Lumen size:	27.9 (10.1)	24.2 (10.3)	20.3 (5.7)
Wall thickness:	3.1 (0.8)	2.6 (1.3)	2.0 (0.5)
Coarseness:	0.341 (0.025)	0.278 (0.020)	0.221 (0.012)

All units in micrometers ecxept coarseness in mg/m

Figure 59. A schematic drawing of relative average cross-sectional fiber dimensions in the long fiber fractions (R14) of newsgrade TMP from saw-mill chips (SM), regeneration cuttings (RC) and first-thinnings wood (FT), based on microscopical analysis. Average lumen sizes base on calculated values. Numbers in brackets indicate the standard deviation between samples.

Fiber Coarseness, Diameter and Wall Thickness

As a measure of average fiber cross-sectional fiber wall area, the above mentioned reduction is also true for TMP *fiber coarseness* of the long fiber fraction (R14). This is shown in Figure 58. The fibers of pulp first-thinnings (FT) thermomechanical pulp were finer than those of RC and especially SM pulps, as shown in Fig. 59 and Table 24. Useful data on the development of selected fiber dimensional properties during refining can also be obtained from Appendices 5–8. If average fiber coarseness is compared as a function of pulp freeness (CSF), the same ranking of the TMPs made from different type of Norway spruce wood exists. When examined at constant 100 ml freeness (CSF) level, FT pulp had an mean coarseness value of 0.248 mg/m, whereas those for RC and SM pulps were 0.295 mg/m and 0.348 mg/m, respectively. Herewith obtained values can be considered as typical, or at least within the range of publication paper grade TMP from northern spruces (Laamanen 1983, Härkönen et al. 1988, Quick et al. 1991).

The character of wood raw material has remained in pulp, since the average fiber diameters of the long fiber fraction (R14) newsgrade end-use pulps were in the same order as those in original wood raw-material (see Figs. 47 and 59). *Thus, with regard to fiber cross-sectional dimensions, hypothesis 5 is supported* (see Section 2.11.3). SM pulp had the widest fibers, being 34.1 µm on average, whereas the values for RC and FT pulps were smaller, 29.4 and 24.3 µm. Values for the

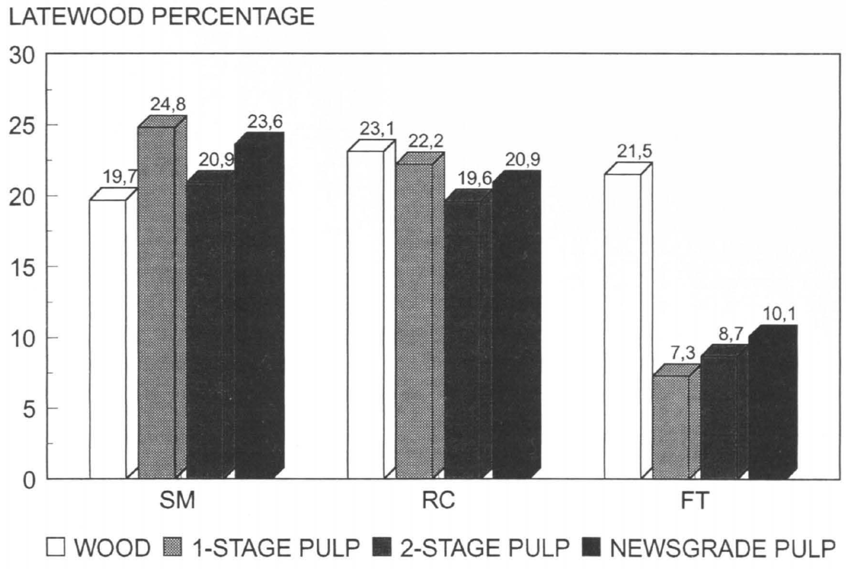


Figure 60. Average latewood contents, expressed as weight percentage, in the long fiber fractions (R14) of thermomechanical pulps made from diffrerent wood raw materials. SM = sawmill chips, RC = regeneration cuttings, and FT = first-thinnings wood.

fiber wall thickness were 3.1, 2.6 and 2.0 µm, respectively. The following figure shows that average cross-sectional dimensions of the obtained pulps (Fig 59). Average lumen diameters were not determined. Instead, calculated values are given.

Like in the case of fiber coarseness, average fiber diameter values for the whole pulps are naturally lower, since they are composed of numerous smaller particles in addition to whole, intact fibers. Moreover, since there exists a very good relationship between the softwood fiber length and size (or volume), the long fiber fractions usually contain not only the longest but also widest fibers from each wood raw-material. In other words, the long fiber fractions of thermomechanical pulps include largely fibers from the outer stem parts, but measurements for the average dimensions of wood fibers include all tracheids. Therefore, average cross-sectional fiber properties of pulp long fiber fractions can be numerically greater, equal, or smaller than the average values for original wood raw-material.

Latewood Content

The earlywood/latewood ratios in the long fiber fractions (R14 and 14/28) of TMPs made from different spruce raw-materials are shown in Appendices 4–7. The latewood contents, expressed as weight percentages, in the long fiber fraction (R14) of SM, RC, and FT newsgrade end-use pulps were 23.6 %, 20.9 % and 10.1 %, corresponding values for the P14/R28 fraction being 14.3 %, 12.9 % and 5.9 %. The *latewood content* was exceptionally low in pulps made from first-thinnings wood. It has to be remembered, though, that latewood definition in juvenile wood, consisting a major part in first-thinnings wood, does not obviously follow the Mork's traditional definition (Timell 1985). The above mentioned percentages were calculated from the results of microscopical counting, using the same weight factors as used in Laamanen (1983) for spruce TMP.

It should be noted that the actual latewood percentage in TMP long fiber fractions did not reflect that in the original wood raw materials. In all pulps, but FT pulps, the content of latewood in the long fiber fractions decreased somewhat during refining, i.e. from the 1st to 2nd stage. The latewood content in FT pulp long fiber fractions were quite stable or showed rather a slight increase as more energy was applied to pulps. This is shown in Figure 60. However, the relative latewood contents in end-use pulp R14 fiber fractions were on average over 10 % higher than in the second-stage pulps. It should be noted that end-use pulps include all three refining lines as well as rejects refiners. But most importantly, the trend of decreasing latewood content for SM and RC pulps, and rather the opposite for FT pulp, was parallel in both R14 and P14/R28 fiber fractions.

Fibrillation Index, Specific Filtration Resistance and Specific Sedimentation Volume of Particle Fractions

Not only the proportion of different pulp particle fractions, as reported earlier, but the quality of these fractions can have a great impact on the papermaking potential of a mechanical pulp. Fibrillation is a structural modification along the fiber wall, giving the mechanical pulp fibers a high bonding capacity as well as contributing to good end-product printing properties. External fibrillation of the fiber wall is to a greater extent a characteristics of groundwood type mechanical pulps, and in TMP the long fibers tend to be poorly fibrillated largely due to thermomechanical pulping process conditions (see Sections 2.1.3 and 2.1.4). Fibrillation indexes (Table 24) determined from end-use pulp long fiber fractions (P14/R28) were relatively high in all pulps. Somewhat lower fibrillation index values for TMP fiber fractions have been reported by other investigators (Laamanen 1983, Paulapuro and Laamanen 1988). The highest value was obtained in pulp made from sawmill chips (SM), being 60 %. The RC and FT pulp long fibers showed lower degree of external fibrillation, the corresponding value being 44 % for both pulps.

In addition to fibrillation index, which characterizes the TMP long fibers, the *specific filtration resistance* and *specific sedimentation volume* is often used in characterizing the quality of the fractions. The former was determined in order to obtain indirect information of the middle fractions (P48/R200) and the latter was used to characterize the fines material (P200) in pulps. Results are shown in Table 24. Apparent filtration resistance in the Bauer-McNett middle fraction of the three different end-use pulps were 236 m/kg for SM pulp, 313 m/kg for RC pulp, and 152 m/kg for FT pulp. Being an indirect measure of the specific surface in that fiber fraction, a higher numeric resistance value always indicates a greater specific surface, at the same particle length level. Thus, RC pulp ranked the best, whereas FT pulp had the poorest potential in this respect. However, this method is tend to be very sensitive to particle length, which, in fact, deviated much in the case of three pulps. Like above, also in the case of specific sedimentation volume, the higher obtained numerical value refers to better potential of the pulp's fines fraction. Very small difference was found in the specific sedimentation volume between end-use pulps manufactured from different type of spruce fiber. The values were 513, 526 and 501 dm^3/kg for the SM, RC, or FT end-use pulps. Again, RC pulp showed to have more bonding potential than the other pulps.

3.4.2.3 Qualitative Analysis on TMP Particle Properties

Visual Analysis of Fiber Quality – SEM and Light Microscopy

A commonly used method to analyze the morphology and characteristics of different mechanical pulp fractions is to examine SEM and light-microscope micrographs taken from these fractions. However, since in one gram of mechanical pulp there is a few million fibers, the limitations of this methodology should be borne in mind when interpreting the information obtained in this way. In this study, the light microscopy allowed the visual confirmation of the fiber composition in long fiber fractions of SM, RC and FT pulps and sheets made out of the whole pulps, whereas scanning electron (SEM) microscopy was employed to provide increased knowledge of the surface development of the individual components in the long-fiber fractions. Three series of photographs are presented. In the first, presented in Appendix 9, low magnification views obtained with light microscopy confirm the gross morphological features of the TMP long fiber fractions (14/28), found already earlier in quantitative analysis of pulp fibers. SM, RC, and FT commercial newsgrade pulps as well as pulps from the first and second refining stages were examined. On an average, SM pulp fibers are larger than RC fibers, the FT fibers being the smallest and consisting largely of juvenile wood fibers. *In terms of fiber morphology, hypothesis 5 is well supported* (see Section 2.11.3).

In the second set (Appendix 10) a high magnification SEM micrographs are presented from the same origins of fiber as mentioned above, but taken from the surfaces of single fibers. It is clearly visible and observable that after the first thermomechanical refining stage, where relatively low energy has been applied to fibers, the fiber separation from the wood matrix has occurred mainly along the combined middle lamella, leaving the fiber wall comparatively intact, the appearance which is typical for thermomechanical pulp fibers. The close examination also confirmed the fact that TMP long fibers are commonly less fibrillated than groundwood pulps (GW and PGW), but more peeled-off showing ribbons and lamellae-like material from the outer cell wall, as more refining energy is used (Jackson and Williams 1979, Paulapuro and Laamanen 1988). Typical interfiber bordered pits as well as pits leading to ray parenchyma of Norway spruce, are visible in majority of SEM micrographs.

Appendix 11 shows cross-sections of sheets made from the three end-use TMPs made from different type of spruce pulpwood. Again, the range of morphological features present in the pulps can be observed. A sheet made from SM pulp, consists of fibers that are largely thick-walled and uncollapsed. In FT pulp, being the other extreme, the fibers have clearly smaller cross-sectional dimensions, whereas the RC pulp exhibits the largest variety of fiber types in its cross-section.

3.4.2.4 Pulp Strength Properties

Compared to other pure mechanical pulps, such as SGW and PGW, thermomechanical pulps have good overall strength characteristics largely due to their high long fiber content. Commercial news-grade TMPs manufactured from sprucewood are reported to have typically from about 50 to 150 % better tear and from about 15 to 45 % better tensile index, than stone groundwood, which, in turn, tend to have poorest strength properties of all mechanical pulps (see e.g. Lindholm 1981a,b and 1984, Jackson 1985, Paulapuro and Laamanen 1988). Thus, TMPs are often favoured for the manufacture of *wood-containing printing and writing papers*, because the amount of more expensive chemical reinforcement pulp can be kept minimal in the paper machine fiber furnish. Since the strength of newsprint still has high priority, particularly when produced at high paper machine speeds and for high printing press speeds, the SM, RC, and FT pulps are valuated as newsprint furnished according to their strength properties.

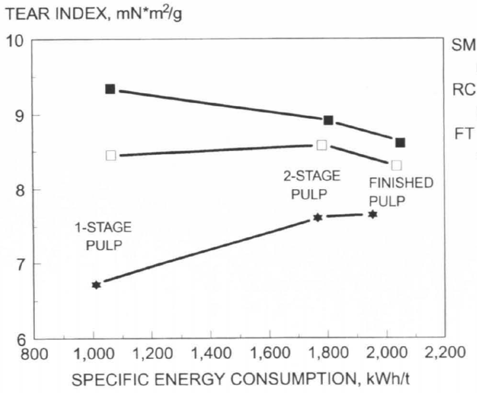


Figure 61. Pulp tear index as a function of refining energy. On an average, thermomechanical pulp made from sawmill chips (SM) had the higher tear index than pulp made from regeneration cuttings (RC) which, in turn, had significantly higher tear index than that of pulp made from first-thinnings (FT)

Tear Strength

Regardless of whether the comparison is made as a function of freeness, power consumption, or sheet apparent density, the tear index of the SM pulps is clearly greater than that of the RC pulps, which, in turn, was considerably higher than that of FT pulps, as assumed in hypotheses 2–4. In fact, the tear strength of the weakest end-use pulp, i.e. FT pulp, did not meet the company production quality specification value of 8.2 mN·m²/g. Figures 61 and 62 show the average development of tear index as a function of the specific energy consumption and freeness. The influence of pulp fiber length distribution is obvious in the primary and secondary refining stages.

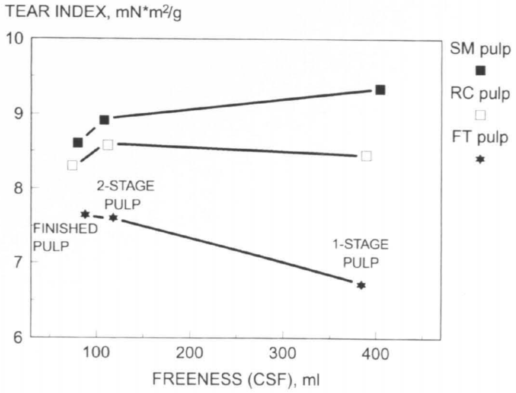


Figure 62. Pulp tear index as a function of freeness (CSF) level. On an average, thermomechanical pulp made from sawmill chips (SM) had the higher tear index than pulp made from regeneration cuttings (RC), which, in turn, had significantly higher tear index than that of pulp made from first-thinnings (FT)

The obtained tear index values from the secondary refining, interpolated to 120 ml freeness level, were from the strongest to the weakest pulp 9.03, 8.54, and 7.60 mN·m²/g, which values are well in the range of commercial spruce thermomechanical pulps (Härkönen et al. 1988, Haikkala et al, 1990, Brolin and Noren 1993, Höglund and Wilhelsson 1993). The development of tear strength during refining showed slightly different patterns for all three pulps, highlighting the differences in the type of fiber of SM, RC, and FT woods. *The above is well in accordance with the hypothesis 2–4* (see Section 2.11.3).

Tensile Strength

Tensile indexes for the trial pulps of this study, i.e. 1-stage, 2-stage, and end-use newsprint thermo-mechanical pulps, are given in Figs. 63 and 64, as a function of specific energy consumption and freeness (CSF), respectively (see also Appendices 4–7 and Table 24).

In all pulps, the tensile index generally increased along with increasing applied refining energy, i.e. increasing degree of fiber development of which main purpose is to enhance pulp bonding properties. The only exception of that rule was FT end-use pulp, which showed a decrease after refined rejects were added. Irrespective whether plotted with pulp energy consumption or freeness, TMP

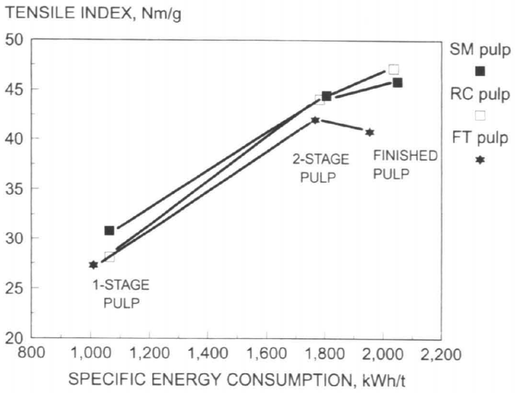


Figure 63. Tensile indexes of the trial pulps as a function of refining energy. In all pulps, the tensile strength increased as more refining energy was applied to increase pulp bonding properties. On an average, thermomechanical pulp made from first-thinnings (FT) had the poorest tensile index. End-use pulp made from regeneration cuttings (RC) had the highest, and pulp made from sawmill chips (SM) performed second best in this respect.

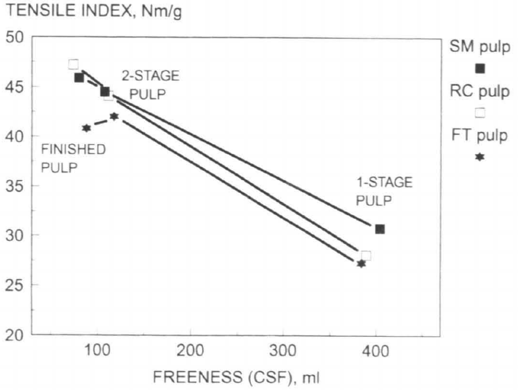


Figure 64 Tensile indexes of the trial pulps as a function of freeness. On an average, thermomechanical pulp made from the first-thinnings (FT) had the poorest tensile strength at all freeness levels. For the news-grade end-use pulps, TMP, produced from regeneration cuttings (RC) had slightly better tensile properties than the pulp made from sawmill chips (SM).

manufactured from the first-thinnings wood gave the poorest tensile properties. The average tensile index obtained for FT newsgrade end-use pulp – 40.8 Nm/g – was even below the company production quality specification, namely, >42 Nm/g. Corresponding values for SM pulp, was 45.9 Nm/g, and for RC pulp 47.2 Nm/g, this being the best performer.

When compared at a constant freeness level of 120 ml (see Appendix 7), and determined from line-A secondary refiner discharge, after screening, the average tensile index of SM pulp, 44.1 Nm/g, was slightly higher than that of OG pulp, 43.8 Nm/g. Here, again FT possessed the poorest performance with its 41.9 Nm/g tensile index. *Differences found in tensile strength are in line with hypotheses 2–4, except RC pulp showed best overall performance.*

Tensile stretch (or elongation) values, being indicative of the ability of paper to conform to a desired contour, for the trial pulps of this study are shown in Table 24 and Appendices 4–7. The RC pulp showed the best fiber network extensibility, by the value 3.8 %, whereas SM pulp was the poorest and FT pulp fell between the two extremes in this respect, these values being 3.1 % and 3.4 %, respectively.

Bursting Strength

Bursting strength is widely used as an measure of resistance to rupture in many kinds of papers, for instance, in newsprint, as it appears to simulate some use requirements. It is known to correlate with the tensile strength and elongation, but also with pulp fiber length. Most often burst is expressed as a *burst index*, which facilitates the comparisons at different paper grammages. The following figure (Fig. 65) shows burst indexes as a function of specific energy consumption of 1-stage, 2-stage, and end-use thermomechanical pulps made from SM, RC, and FT wood raw materials.

Generally, burst strengh of all pulps increased with increasing energy applied to pulps. Strong increases in burst index were initially achieved from the primary to the secondary refining stages. As the refined rejects are added up, i.e. when this pulp property is determined from the end-use newsgrade pulps, further increases were achieved.

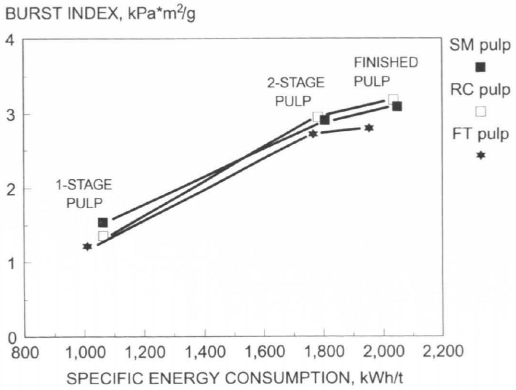


Figure 65. Pulp burst index as a function of refining energy. On an average, thermomechanical pulp made from the first-thinnings (FT) had the poorest burst strength, whereas that in news-grade end-use TMP produced from regeneration cuttings (RC) was very similar than in pulp made from sawmill chips (SM).

The pattern is more or less identical, when burst indexes are compared as a function of pulp freeness. On an average, thermomechanical pulp made from the first-thinnings (FT) had the poorest burst strength, thus, supporting hypothesis 4, whereas that in news-grade end-use TMP produced from old-growth regeneration cuttings (RC) was very similar than in pulp made from sawmill chips (SM). The average burst indexes of end-use pulps ranged from 2.80 kPa·m²/g for FTpulp, to 3.18 kPa·m²/g for RC pulp, the corresponding value being 3.09 kPa·m²/g for SM pulp. Results are consistent with those obtained elsewhere for commercial spruce newsgrade TMP (Lindholm 1981a, Härkönen et al. 1989, Haikkala et al. 1990). However, no dramatic diffrences were found in burst indexes, when determined from the secondary refiner discharge (line A) at a constant freeness of 120 ml. The burst index of RC pulp was 2.88 kPa·m²/g, that of SM pulp 2.86 kPa·m²/g, while FT pulp had the value 2.71kPa·m²/g.

3.4.2.5 Pulp Optical Properties

The performance specifications of printing papers require that the end-products have a certain brightness and opacifying properties, because they are critical for the paper printing properties and overall outward appearance. The requirement of *brightness* and *opacity* in paper, in turn, have almost a direct bearing on these properties in used pulp furnish. Thus, it is important that the pulp producer and papermaker combine their understanding of the factors contributing to the development of preferred sheet qualities. When it comes to the properties of the mechanical pulps, it is well justified to use the pulp *light scattering coefficent* instead of opacity, because it is independent of sheet basis weight and at a given pulp brightness unambiguosly reflects the opacity potential of the pulp (Paulapuro and Laamanen 1988). Pulp light scattering properties together with its light absorption properties determine the brightness of the sheet.

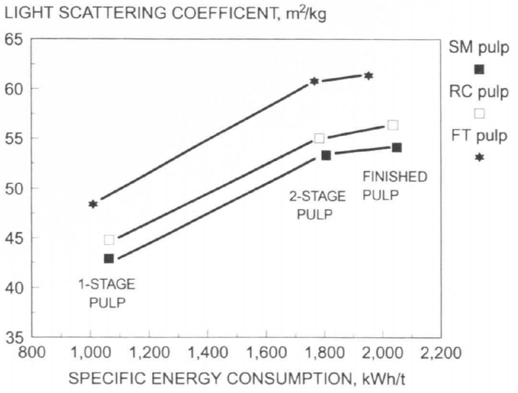


Figure 66. Light scattering properties as a function of the specific energy consumption (SEC) of the 1-stage, 2-stage, and newsgrade end-use thermomechanical pulps made from different sprucewood assortments. FT pulp had clearly the best light-scattering power, whereas TMP from sawmill chips had the poorest.

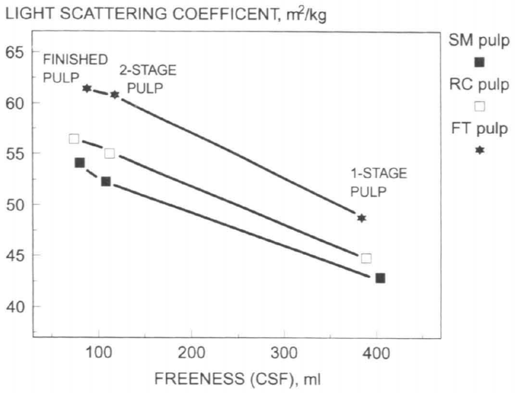


Figure 67. Light scattering properties as a function of the freeness of the 1-stage, 2-stage, and newsgrade end-use thermomechanical pulps made from different sprucewood assortments. First-thinnings (FT) pulp had clearly the best light-scattering power, whereas TMP from sawmill chips (SM) had the poorest.

The light scattering coefficent, opacity, and brightness, of the 1-stage, 2-stage and newsgrade thermomechanical pulps made from the three investigated wood assortments are given in Figs. 66–71 as a function of SEC and freeness (CSF). All values are determined from 65 g/m² laboratory sheets that were made using recirculated white water.

Light Scattering Coefficent

Significant differencies in the light scattering power existed between pulps made from different sprucewood assortments. In all three pulps – made from either SM, RC or FT wood – the value of the light scattering coefficent increased with both increasing refining energy input or decreasing pulp freeness. Irrespective of whether expressed as a function of the former or the latter, FT wood gave pulp with superior light scattering properties compared to the other pulps, of which the SM pulp had the poorest light scattering. The best obtained light scattering value was 61.4 m²/kg, found in FT end-use pulp. Comparable values were significantly lower for the two other pulps. When determined from the secondary refiner discharge (line A) at a constant freeness of 120 ml, the light scattering coefficent of FT pulp was 60.7 m²/kg, whereas that for RC and SM pulps was dramatically lower, being 54.9 and 53.2 m²/kg, respectively (see Appendix 7). *The above clearly confirms that hypotheses 2–4 are true with regard to pulp light scattering power* (see section 2.11.3).

Light scattering coefficient values varying normally between about 50 and 65 m²/kg, have been reported in literature for printing grade thermomechanical pulps made from Norway spruce and other spruces (Härkönen et al. 1988, Haikkala et al. 1990, Braaten et al. 1993, Höglund and Wilhelmsson 1993). Thus the obtained values are not untypical, but they reflect the normal variation, attributable to wood properties and pulping conditions.

Opacity

Good paper opacity is the most requested printability characteristics in mechanical pulps for newsprint (Hooper 1988, Hoekstra et al. 1991). However, it should be noted here, that opacity of TMP laboratory sheets does not necessarily reflect that property in the paper end-product, and therefore pulp light scattering value should be used instead for comparisons between different fiber furnishes. Opacity improves as light scattering and paper basis weight increase.

No statistically significant differences in opacity of either 2-stage or end-use pulps, were found between the SM, RC, or FT pulps. The above is true, whether the opacity is plotted with the pulp specific energy consumption or freeness. In early stages of refining, i.e. after the primary refiner, where fibers are being separated from the wood matrix but no extensive surface development is expected to occur, FT pulp had slightly better opacity than RC pulp, whereas SM pulp, in turn, had the lowest opacity. In addition to the following figures (Figs. 68 and 69), data on average opacity values is shown in Table 24 and Appendices 4–7.

The above results seem to be well in accordance with Braaten et al. (1993) who have studied the effect of different Norway spruce wood assortments on the properties of TMP. In this pilot-plant experiment the average opacity at 2000 kWh/t SEC level varied only from 92.3 to 92.7 % between thinnings, toplogs, but/middle logs and slabwood, those differences being not statistically significant. On the other hand, thinnings pulp had though 4.5 m^2/kg higher light scattering coefficent at the same SEC level, than did TMP from sawmill chips, having the poorest value of 53.4 m^2/kg.

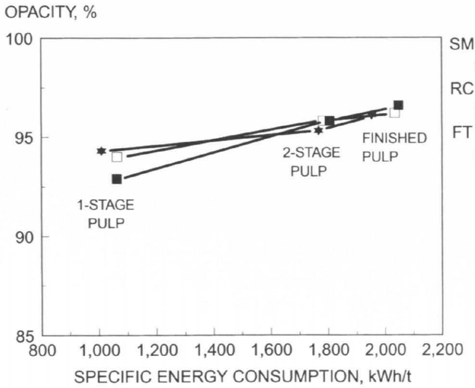


Figure 68. Pulp opacity as a function of the specific energy consumption (SEC) of the 1-stage, 2-stage, and newsgrade end-use thermomechanical pulps made from different sprucewood assortments. Although First-thinnings (FT) pulps had the best overall performancy in terms of opacity, no statistically significant differences were obtained between newsgrade end-use pulps.

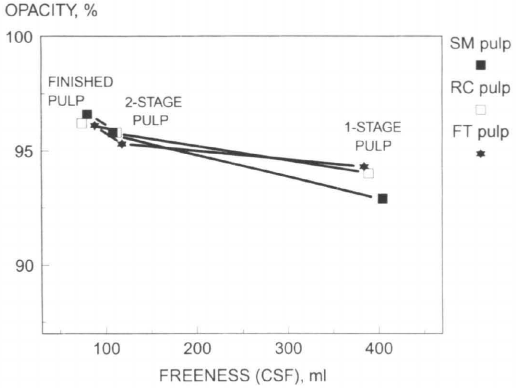


Figure 69. Pulp opacity as a function of the freeness of the 1-stage, 2-stage, and newsgrade end-use thermomechanical pulps made from different sprucewood assortments. First-thinnings (FT) pulps had the best overall opacity, whereas TMP from regeneration cuttings (RC) had the poorest.

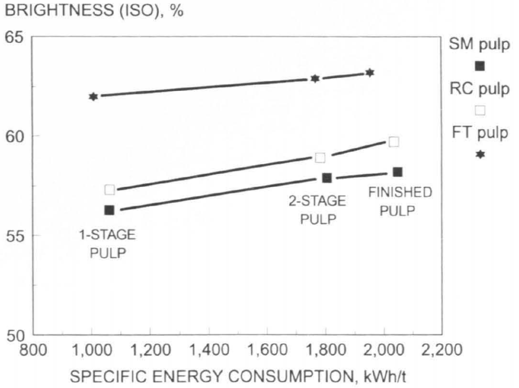


Figure 70. Brightness (ISO) as a function of the specific energy consumption (SEC) of the 1-stage, 2-stage, and newsgrade end-use thermomechanical pulps made from different sprucewood assortments. FT pulp had clearly the best brightness, whereas TMP from sawmill chips had the poorest.

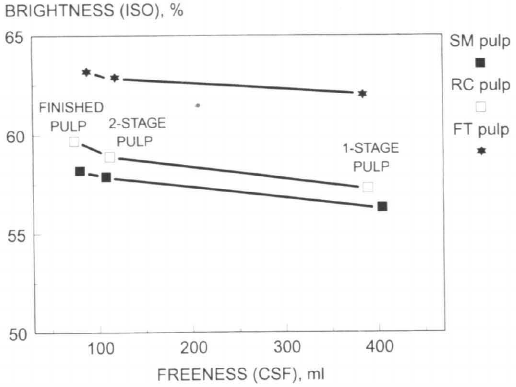


Figure 71. Brightness (ISO) as a function of the freeness of the 1-stage, 2-stage, and newsgrade end-use thermomechanical pulps made from different sprucewood assortments. First-thinnings (FT) pulp had clearly the best brightness, whereas TMP from sawmill chips (SM) had the poorest.

Brightness

Mechanical pulp brightness is a function of its light scattering and light absorbing surfaces in pulp, and thus, mainly dependent on fiber composition and the quality and quantity of the fines particles. In all mechanical pulping processes, due to process conditions, discoloring compounds called chromophores are formed in pulp particle surfaces, increasing the pulp light absorption and decreasing therefore the brightness. Also wood brightness (or whiteness) can have its influence on pulp brightness, mainly via wood's light absorbtion properties, which phenonmenon is discussed later, in Section 3.4.1 (Höglund and Wilhelmsson 1993).

A similar pattern than in the case of pulp light scattering properties, was observed for pulp ISO-brightness (Figs. 70 and 71). Namely, the brightness value increased as a function of fiber development, i.e. increasing refining energy or fineness of pulp. *Furthermore, the final ranking of pulps made from different raw materials was also the same, confirming the statements of pulp brightness in hypotheses 2–4* (see Section 2.11.3). End-use pulp from first-thinnings (FT) wood gave sovereignly the best brightness, 63.2 %, this value being 3.5 points (ISO) higher than that of RG pulp, 59.7 %. The lowest newsgrade end-use pulp brightness, 58.2 %, was obtained with the use of sawmill chips (SM) as TMP raw-material. When 2-stage pulps from the "control" refining Line A were compared, at the constant 120 ml freeness level, the corresponding brightness values were 62.9, 58.8, and 57.8 % (see also Appendix 7). It should be borne in mind that the newsgrade end-use pulps are not being bleached at EG Varkaus mill, and thus, they enter the paper machine as they are.

3.4.2.6 Sheet Structural Properties

Sheet Apparent Density and Bulk

The *apparent density* of laboratory handsheets provides a useful indirect measure of the ability of the wet formed web to consolidate under an applied load. This property thus represents a complex index of fiber flexibility, degree of fiber packing and extent of interfiber bonding between the fibers after drying (Lindholm 1981a and b, Nordman 1987). In pure mechanical pulps, the obtainable sheet density does not depend much on the type of pulping process, but is more influenced by the size and nature of their particles. Like the pulp tensile strength, which is to a large extent affected by pulp bonding properties, also sheet density has a quite linear relationship with pulp freeness and the amount of fines. In newsprint and related furnishes, pulps giving dense sheets at a given freeness level are preferred, since good sheet consolidation contribute both strength and printing properties. Apparent sheet densities obtained for pulps of this study, are given in Appendices 4–7, and, as

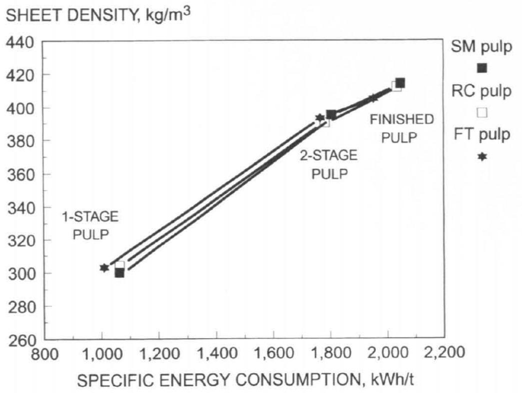


Figure 72. Apparent sheet density as a function of the specific energy consumption of the 1-stage, 2-stage, and end-use newsgrade pulps made from sawmill chips (SM), regeneration cuttings (RC) and first-thinnings (FT). No significant differences were found between the pulp types.

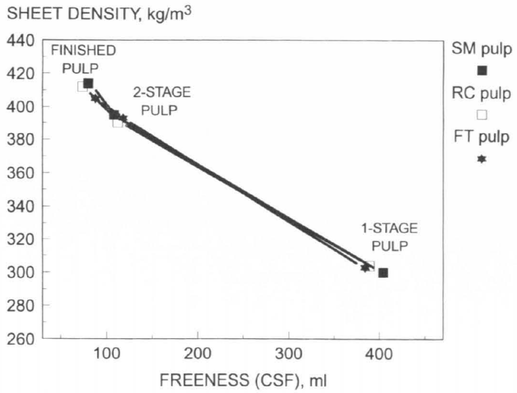


Figure 73. Apparent sheet density as a function of freeness of the 1-stage, 2-stage, and end-use newsgrade pulps made from sawmill chips (SM), regeneration cuttings (RC) and first-thinnings (FT). No significant differences were found between the pulp types.

a function of SEC and freeness, in Figures 72 and 73.

As could have been expected, sheet consolidation, in terms of the apparent density, improved as more refining energy were applied to pulps, but surprisingly, with regards to fiber morphology, no statistically significant differences were found between the pulps from different wood raw-materials. The average apparent sheet densities for 2-stage (Line A) pulps, when determined at constant 120 ml freeness level, were 391 kg/m³ for SM pulp, whereas those for RC and FT pulps were 386 kg/m³ and 392 kg/m³, respectively. Those values can be considered, though, as normal for newsgrade Norway spruce TMP (Mohlin 1979, Kärnä 1986, Haikkala et al. 1990, Braaten et al. 1993).

In wood containing publication papers, it is the mechanical pulp component, from which the paper gains *bulk*. In practice, sheet bulk is not a measure of pulp quality, but can indirectly give useful information of pulps potential in papermaking. There is a fairly general agreement that the bulk, which is the reciprocal of sheet density and a measure of the solid fraction of the sheet, is highly correlated with the mechanical pulp particle distribution. As pulp freeness decreases with increasing amount of energy applied in thermomechanical pulping, the sheet bulk decreases. However, at the same fines and middle fractions content, the morphology of long fibers is the main factor influencing the bulk of newsprint. As there is a continuous trend towards lower basis weights in publication papers, as already discussed in the introductory section (Section 1.1), papers will be not denser but either bulkier or of lower caliper, and should still have excellent strength and printing properties.

Irrespective to fiber morphology, because of the greater proportion of long fibers and smaller amount of fines, it could have been expected that sheets made from SM pulp were bulkier than especially FT pulp sheets. However, the results show no practical differences in bulk between SM, RC, or FT pulps, if plotted either with freeness or SEC. When the 2-stage pulps were examined at constant 120 ml freeness level, bulk for SM pulp was 2.61 dm³/kg, whereas those for RC and FT pulps were 2.63 dm³/kg and 2.58 dm³/kg. Values of bulk for the 1-stage, 2-stage and end-use pulps are showed in Table 24 and Appendices 4–7.

Smoothness and Porosity

In the case of newsprint, good *smoothness* of the paper surface along with low *porosity*, are extremely important properties required for good printability. In mechanical pulps, sufficent fines and middle fractions provide not only good formation and opacity, but also high smoothness and low porosity (Hooper 1988, Harris 1993) Furthermore, in newsprint, being a relatively low grammage paper, where the proportion of mechanical pulp component is high and no fillers or supercalendering are used, the role of long fiber fraction is even more highlighted. Namely, both finer particle size distribution and finer fibers, in terms of fiber diameter, length and cell wall thickness, are expected to give a better smoothness as well as lower porosity. The roughness of newsprint sheet is determined therefore mainly by the proportion of large, stiff and inflexible fibers in the sheet surface. However, it can be partly offset with selective treatment of the long fibers in thermomechanical pulping process in order to make them more flexible and collapsible (Hooper 1988, Corson 1992, Harris 1993). Porosity of sheet is even more complicated property than smoothness, and is known to be a function of several factors. Here too, finer particles with good bonding ability in pulp are expected to produce less porous paper.

With regards to variation in fiber properties between SM, RC and FT pulps, no related findings were made neither in the case of surface smoothness, expressed as Bendtsen-roughness, or porosity, expressed as air permeability (Bendtsen). *This is in conflict with hypothesis 5* (see Section 2.11.3). The obtained values of these properties for different pulps are shown in Table 24 and Appendices 4–7.

In end-use pulps, SM pulp had only about 4 % greater roughness value than FT pulp. Moreover, in contrary to what could have been expected, FT pulp had 13 % greater surface roughness, and thus, poorer smoothness, than RC pulp. However, these values are generally in agreement with those, that have been obtained for publications paper grade TMP from Norway spruce (Vaarasalo et al. 1981, Paulapuro and Laamanen 1988). When pulps are plotted with freeness, sheet roughness values for 2-stage pulps at constant 120 ml freeness (CSF) were 420 ml/min for SM pulp, 460 ml/min for RC pulp, and 315 ml/min for FT pulp, which was the best performer. Rejects refining seemed to offset the above differencies in sheet smoothness.

In newsgrade end-use pulps, FT pulp sheets had over 40 % Bendtsen air permeability value, than SM pulp, being thus more porous. Furthermore, the porosity of sheets made from RC pulp was about 8 % higher than SM pulp air permeability value of 120 ml/min. In the second stage pulps, determined at 120 ml constant freeness, it was the RC pulp, with 290 ml/min value, which was most porous. SM pulp showed again to be less porous with its 235 ml/min air permeability value, FT pulp being between these two extremes with 275 ml/min. The obtained values are, however, well in accordance with those found for printing grade TMP manufactured from Norway spruce (see e.g. Kärnä 1986, Paulapuro and Laamanen 1988, Haikkala et al. 1990). The above gives strong evidence that TMP made from sawmill chips (SM) can also have relatively low porosity. Moreover, it was evident, like in the case of sheet smoothness, that porosity is mainly determined by other factors, than the morphology of long fibers.

3.4.2.7 Pulp Extractives Content

Pulp extractives content is known to be reflected by to a large degree that in original wood raw-material (Tay and Manchester 1982, Kappel et al. 1991, Suckling 1993). Generally, high extractives content in thermomechanical pulps equals low brightness, high color reversion, poor bonding, and poor absorbency. In practice, however, the main problem of mechanical pulp extractives is their contribution for the "pitch" (or resin) problem in paper making (see Section 2.10.2). Secondly, they are the major source of toxic compounds in effluents (Wong 1981, Hoel and Aarsand 1993). Typically unbleached end-use TMP pulps from spruce have well below 1 % (DCM) average extractives contents (Hartler 1985, Kappel et al. 1991). Average extractives (DCM) content, found in newsgrade end-use pulps manufactured from different sprucewood assortments, are shown below together with those in original wood raw-material (Fig. 74).

FT pulp had clearly the lowest content, 0.43 %, compared to the highest value, 0.83 %, obtained with SM pulp. RC pulp fall between those two, having extractives content of 0.57 %. Overall extractives contents in all of the pulps can be considered to be quite low, but still within a typical

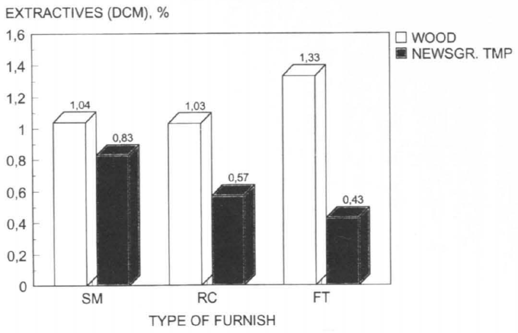


Figure 74. Average extractives (DCM) contents in the newsgrade end-use thermomechanical pulps and in the original wood raw-material (SM, RC, and FT woods). No actual relationships were obtained between the content of extractives in wood and pulp.

range of newsgrade unbleached TMP, manufactured from Norway spruce. Moreover, no actual relationships were obtained between the content of extractives in wood and pulp. It should be noted that the chemical composition of extractives was not determined.

3.5 Discussion

Since the sample was limited to wood from trees in Varkaus area, southern Finland, the present results must be regarded as explanatory and not as representative of the species Norway spruce or any other conifer. Therefore, these observations regarding the potential of Norway spruce as a mechanical pulp raw material are probably assignable first of all to newsgrade thermomechanical pulp manufacture at EG Varkaus mill. However, the design of this experiment in terms of sample size, range of wood properties variation and pulping conditions should also allow a comprehensive and comparative general discussion regarding similar subjects.

3.5.1 Influence of Wood Properties

As have already emphasized in Section 1.4 and 3.2, it was not the intention of the empirical study to establish correlations between single wood and pulp properties, because such attempt would be without practical justification. Instead, wood type was chosen as a base, being a combination of several wood factors. Namely, distinctly different pulpwood assortments – SM, RC, and FT woods – were formed basing on the wood and fiber properties presumed to have importance in TMP manufacture. Being so, hypotheses of the response of each wood assortment to thermomechanical pulping were formed, and tested in the empirical study. The statistically and commercially significant differences in pulp properties found in pulps made from the above wood raw materials are then rationalized in terms of their intrinsic wood and fiber properties, determined from the raw materials, and the pulping mechanism involved, that is, TMP. The effect of each wood and fiber property is being discussed separately. The foundation for interpreting the influences of wood properties on TMP manufacture, is the results of the theoretical study (Chapter 2) and the existing knowledge in literature. It should be mentioned that the literature is not very abundant, as far as both Norway spruce and TMP are involved. The potential use of each pulp type – SM, RC, and FT pulps – for the manufacture of newsprint is discussed.

Chip Configuration and Bark Content

Irrespective to intrinsic wood and fiber properties, chip size homogenity can have a dramatic impact on TMP and refiner pulping and therefore chips should have lowest possible proportion of undersize and oversize fractions (Hartler 1985, 1994). In this study, the chip quality, referred to as prime chips content and its variation, can be considered very uniform between the wood types (see Fig. 42 and Appendices 1–2). The fact, that the average chip dimensions differ though, but with relatively low standard deviation, emphasize only the circumstance that the wood properties of raw materials in question differ considerably from each other. This is due to expected differencies in moisture content, wood basic density and some other wood properties, which have their influence on the chipping operation (Hartler 1994).

The effects of chip size on TMP properties and pulp energy consumption has been studied by Hoekstra et al. (1983), Hartler (1985), Brill (1985) and Eriksen et al. (1981) for Norway spruce and some other northern softwood species. As with kraft pulping, along with overall homogenity, chip thickness plays a decisive role in TMP pulping, although via different mechanisms. According to Hartler (1985), the overthick fraction not passing the 8 mm slot width can very well constitute up to 15 % of the total in some pulping systems and contains the major part of the knotwood. This fraction is likely to be inadequately heated and can disturb chip density/feeding. The removal of this fraction has been found to be beneficial to pulp quality. The specific energy requirement of TMP to reach a given freeness has been noticed to increase from the average accept chip thickness of 1.5 mm to 6.0 mm. Along with increased applied energy, the pulp bonding properties increased as well. The optimum combination of TMP strength and energy consumption would be obtained with 3–4 mm thickness range (Hoekstra et al. 1983). The chip material of this study fulfilled quite well this requirement, since the average chip thicknesses varied from 3.86 to 4.25 mm

TMP tear index should not be much affected, when the prime chip content is above 85 %, as was the case here (Brill 1984). However, it has been shown that tear index increases in a linear manner approximately 10 % when the average length of chips increases from 15 mm to 25 mm. This is due to corresponding increase in average chip fiber length (or long fiber content), when longer chips are used (Eriksen et al. 1977). The effect of average chip length on the reduction of average fiber length in TMP chips, is expected to be somewhat different for SM, RC and FT chips, depending on the original average fiber length of wood. This was already discussed in the theoretical study (Section 2.4.2 , Fig. 18). Fiber length reduction in chipping has naturally occurred in all three wood types, namely, SM, RC, and FT woods. But since the range of average chip length in all raw-materials was as low as 15.8–18.1 mm, the fiber length must have been reduced most dramatically in the case of sawmill chips (SM) and some of its strength potential was lost due to relatively short chips. As the measured average fiber length in SM chips was about 3 mm, it is known that average fiber length in outer parts of the *Picea abies* sawlogs well exceed 3.5 mm. As has become apparent from the foregoing, no other major negative effect could be seen, in addition to the above discussed fiber length reduction and associated loss in TMP tear strength.

TMP process is said to allow only 0–1 % bark in wood chips, and groundwood process even lower percentages without major effects in pulp quality (Erickson 1979, Brill 1985). Bark in TMP tend cause loss of brightness and pulp strength, and more importantly, is a major constituent of dirt specks in paper. However, severe effects occur only at considerably higher bark contents as observed for Norway spruce by Annergren and Hägglund (1979), Hartler (1985), Abadie-Maumert (1985) and Brill (1985). In the light of the above, it is thus concluded that there was no major effect on pulp quality caused by wood bark in any of the wood assortments, having on an average only from 0.0 to 0.1 % bark. Although the bark contaminants were not determined from pulps, in terms of dirt count, or any other measure, it is presumed that no great differences remained between the three pulps, after processing, i.e. washing, screening, and cleaning. However, it should be mentioned, that at the same degree of bark cleanliness, as was the case between RC and FT roundwood, the wood loss occurring during drum debarking process is expected to be greater for the latter. This is due to the fact that small-sized, tapering bolts, especially top ends and are known to be prone to wood loss (Erickson 1979, Niiranen 1985)

Basic Density

In this study, significant differences were found in the average basic density between the three raw-material assortments. The obtained basic densities were not predictable at all and can hardly be considered to represent systematically wood densities, obtained from the SM, RC, and FT sources. This is so, because a large variation can exist in this gross wood characteristics, even between close spruce stands in southern Finland. The relatively high basic density of old-growth wood is explained with old age and slow growth rate, which both contribute high basic density. Moreover, the removed raw material assortment for pulping trials consisted of not only dominating stems, but also of supressed stems, which typically can have very high basic densities. The lowest density value for SM wood, when compared with FT wood, can be partially due to growth rate or latewood content. In this investigation, none of the first-thinnings stands showed very fast growth rate, this fact contributing the relatively high basic density of the FT wood.

Unlike earlier believed, the basic density itself cannot be hardly considered a wood quality indicator in pulping, at least not in mechanical pulping, since wood basic density is heterogenous, complex wood property, which give no direct data on fiber properties in a coniferous stem (see 2.4). Since the density variation, in terms of standard deviation, was smaller within the wood assortments (measured from individual chips), than the variation in average basic density between the SM, RC and FT wood, it can be presumed that pulping them separately should have eliminated some of the harmful effects of ununiform wood raw-material on both pulp quality and energy consumption. As another major effect on TMP manufacture caused by the basic density of the studied raw-materials, would be the considerably higher pulp yield from RC wood. Assuming that the weight-based pulp yield is approximately same from all three woods, the yield from OG wood was 7.3 % better than FT wood and even 10.7 % better than SM wood, when calculation is based on purchased roundwood volume. In Scandinavia, the cost wood forms always over 50 % of the total cost of finished TMP (Hoekstra et al. 1991). In the light of this, the production cost for RC pulp would be several percents lower than that with the other pulps.

Moisture Content

It is well known that in any mechanical pulping operation the moisture content of the wood employed should preferably exceed fiber saturation point (FSP). Moreover, it is often recommended that wood should contain a minimum of 40 per cent moisture if mechanical pulp of good quality is to be produced. Mechanical pulps produced from dryer wood are weaker, contain more debris, and can consume more energy (see Section 2.3.2).

In all wood raw materials used in this study, the average moisture content, determined as wet-basis, exceeded 50 % and thus the fiber saturation point. Moreover, in a given wood, minimal moisture variations were observed between the samples during the refining. Much more greater moisture variations in the chip flow just prior to the primary refiners has been reported in literature (Hartler 1977, Hill et al. 1990, Fournier et al. 1992). With a special reference to RC wood, where the greatest source of variation is its relatively moist sapwood and considerably dryer heartwood, the above fact evidences the high degree of mixing and evenness in the chip flow. However, it should be noted here that "micro-variation", that is, the variation between individual chips, was not measured. Relatively high moisture content in each wood assortment is largely due to the fact that Norway spruce stems have higher moisture content during dormant season in the northern latitudes, combined with the absence of wood storage time. In the light of the above, it is assumed that moisture content itself had no major effect on pulp quality or refining energy consumption. However, as in the case of basic density, refining relatively uniform raw materials in terms of moisture content, some improvements in overall pulp quality and energy consumption can be expected.

Fiber Morphology

As has become apparent from the foregoing, the morphology of wood fibers largely determines the pulp quality characteristics that can be obtained from any given raw material (see Sections 2.4, 2.5, 2.6 and 2.7). This discussion refers, however, to TMP quality effects caused by deviation in average fiber dimensions between the three different Norway spruce assortments, that is, SM, RC and FT woods. Höglund and Wilhelmsson (1993), while studying the properties of Norway spruce TMP fibers in a pilot-scale, found that all fiber dimensions are substantially reduced during refining, but the character of wood is well retained into the long fiber fraction. This was also the case in this study. The upper range of the fiber size distribution function, especially the pulp fiber length, is established during the initial process of fiber separation. All unnecessary fiber length reduction that occurs here and in the subsequent stages of fiber development will act to reduce the properties of furnish (May 1973, Kurdin 1979, Corson 1980, Jackson 1985, Karnis 1993). In fact, all three raw materials seemed to respond similarly to refining in the early stages of refining. As expected, fiber length and the proportion of the long fibers were indicative of the tear strength potential of the used raw materials.

Part of the tensile strength deviation between the pulp types is definitely explained with the fiber length factors, since at the same pulp bonding strength the longest fiber gives strongest pulp (Jackson and Williams 1979, Lindholm 1984). However, not only the fiber fraction which comprise about 30 % of the pulp's weight, but more importantly the quantity and quality of the middle and fines fractions largely determine pulp tensile strength. The fiber fraction has both whole fibers and shortened fiber lengths resulting from the fiber fracture that occurs during the pulping process. The middle fraction has short fibers, broken fibers, and lamellae from the fiber wall. Finally, fines fraction contain particulate debris, i.e., middle lamella material and ray cells, and fibrillar material, i.e., fibrils from the fiber wall. It is the individual behavior of the various components, and their synergistic interaction with the other components, both within and between these fractions, that results in the overall performance characteristics of the whole pulp. It should be noted that perhaps for the same reason, no direct correlations between mechanical pulp long fiber cross-sectional dimensions and pulp strength properties have been obtained within a wood species (see Section 2.5).

Sheet density, being indicative of pulp bonding properties, bulk, smoothness or porosity were found to be highly correlated with the applied specific energy, i.e. the fiber development. However, contrary to what could have been expected from the dimensions and relative amount of pulp long fibers (R14), no significant differences were found in any of the above properties. It is therefore assumed that these properties were not determined mainly by dimensions of the pulp fibers, but affected mainly by other factors. This leads to a fact that there is no big difference in flexibility and collapsibility in fibers due to their morphology, and all TMP fibers were relatively stiff. However, in a given volume or weight of wood chips or pulp, there are several times more single fibers in FT wood than in SM wood, these being the two extreme cases. The above naturally contributes to the good optical properties of FT pulp, although the main effects are expected to come from the quantity and quality of fines material.

Latewood Proportion

In Norway spruce stemwood, positive correlations exist between latewood percent and basic density, age of cambium and latewood percent (excluding the juvenile wood), and finally a negative correlation between the year-ring width and latewood percent (Section 2.6). In the light of this, the latewood percentages found in this study for different types of wood raw materials seem to be well in accordance with the above. However, every conclusion should naturally be interpreted with a precaution, because these relationships can applied only to very limited ranges of ring-width, cambium age, geographical areas, and only within some species.

It is known, that latewood content itself has not any single or simple effect on mechanical pulping and pulps. This can be easily understood, because the magnitude of variation in latewood tracheid properties, and more precisely their size, is quite huge not only between different softwood species, but also within a species depending on wood (cambium) age and growth conditions. This is perhaps why very contradictory results and assumptions exist of how these fiber type behave in refining and how do they affect paper strength properties, sheet consolidation, printing properties, etc. (see Section 2.6). Within a more limited range of wood rawmaterial properties, relationships between latewood proportion, and pulp and paper properties could be expected, though. Furthermore, increased requirements for printing papers has very recently given rise to increased research efforts and discussion in attempting to understand more the behaviour and importance of these two extreme fiber types in mechanical pulps and paper end-products, subsequently manufactured from them (Corson 1992, 1994, Corson and Ekstam 1993, Karnis 1993, Hickey and Rudie 1993, Laurent et al. 1993, Lai and Iwamilda 1993, Höglund and Wilhelmsson 1993).

In this study, the actual latewood percentage in thermomechanical pulps did not necessarily reflect that in the original wood raw materials (Fig. 60). Differencies may be partly due to different method of latewood content determination, as described earlier in Section 3.3. However, contradictory results have been obtained how the latewood contents of wood and pulp are related and how this property develops during thermomechanical refining (Laamanen 1983, Rudie et al. 1993, Corson and Ekstam 1993, Lai and Iwamida 1993). The obtained results suggest, however, that the coarser the fiber in a given wood raw material on an average, the better the latewood fibers retain their fiber length, being enriched in the 1-stage pulp long fiber fractions. Furthermore, in two pulps, SM and RC pulps, the relative proportion of latewood fibers then decreased with the successive refining.

The observed phenonmena that FT fibers responded somewhat differently to pulping (see Fig. 59) than other pulps, is very interesting and highlights the fact that these fibers, being mostly juvenile fibers with different size and ultrastructure, do not behave in the same manner during refining. There was insufficient data to determine the mechanisms for the above findings. Furthermore, no direct connections on pulp properties, except with the average fiber coarseness and long fiber content of pulps, can be related to pulp latewood content. For instance, the obtained sheet properties, in terms of sheet apparent density, bulk, sheet porosity and roughness, did not reflect pulp latewood content.

Heartwood Content

It is known that chips from the heartwood and sapwood give different property profiles in the TMP process (Höglund and Wilhelmsson 1993). However, some of the effects can be attributed to high juvenile content in heartwood or some other wood properties, than distinctly related with the heartwood formation.

As could have been expected, the highest content of heartwood, approximately 43 %, was found in old-growth, regeneration cuttings (RC) wood. In other assortments, the effect of heartwood is presumably non-existent, as in SM wood, or very low, as in first-thinnings wood (FT). Since all three wood assortments required approximately same amount of energy, when refined to the same freeness level, it is difficult to assume that the specific energy consumption for RC wood would have been much smaller with the absence of heartwood. In their study, Höglund and Wilhelmsson (1993) found TMP from Norway spruce heartwood to consume actually less energy, than for instance sapwood. Contradictory results exist of the effects of heartwood in mechanical pulp manufacture (deMontmorency 1964, McMillin 1968, Nyblom 1979, Höglund and Wilhelmsson 1993, Bengs and Lönnberg 1994).

Perhaps the only clear effect in the studied pulps, which could be attributed to existence of heartwood, is the higher shives content of RC wood. Namely, end-use TMP from RC wood had 50 % more shives by weight (Somerville) than SM pulp, whereas the corresponding figure was well over 100 %, when compared to FT pulp. The same tendency was obtained with the shives number (PQM), as that for RC newsgrade pulp was about 10 and 25 % higher than for SM and FT end-use pulps. The above is expected to result from extremely dry and impermeable heartwood. There was insufficient data, and it was out of the scope of this study, to determine the effect of this critical newsprint property on the newsprint quality. Better light scattering properties of RC wood compared to SM wood, resulted partially from smaller average fiber size and content of juvenile wood, found in inner parts of RC logs.

Juvenile Wood Content

As already thoroughly discussed in the theoretical study (Chapter 2), juvenile wood in conifers is not any homogenous wood characteristics, but a tissue around the wood pith, in which many wood anatomical, chemical, physical and ultrastructural properties change towards the cambium, with a varying rate that is specific to each property. Thus, its influence is discussed here as a collective property. The existence and increased practical importance of this type of wood has given rise to numerous studies also in the area of mechanical pulping. Bulk of these studies has concentrated on radiata (*Pinus radiata*) and southern pines (*Pinus taeda, Pinus elliottii* etc.), since their noteworthy economical and technical significance to date. In northern softwoods, such as Norway spruce, the juvenile wood is less distinct and its expected influence on pulping less notable. However, some common effects that are reported to be caused by juvenile wood, is the increased optical properties but decreased tear resistance of the mechanical pulps, among them TMP. Other properties, such as tensile strength, burst strength, sheet density, and specific energy consumption, have improved or deteriorated, or no trends has been found. Paper surface properties, such as smoothness and porosity, are usually enhanced due to averagely finer-sized fibers in juvenile wood pulps.

In this study, most of the fibers in first-thinnings wood (FT), can be classified as juvenile fibers and only a minor part of the wood, i.e. tracheids from the oldest growth-rings, was mature wood. Furthermore, the latter wood cannot be considered so distincly as mature wood, in terms of fiber properties, if compared with sawmill chips (SM) wood, being merely mature wood. As long as there is no other major foreseeable wood property, which could explain significant differences in sheet structure, pulp particle size, strength or optical properties, found between FT pulp and two other pulps, it is assumed that the cause is likely the existence of juvenile wood. However, it should be remembered that RC wood contained a small portion of juvenile wood. Because of this, it is easy to understand that RC pulps fell always between FT and SM pulps, with those pulp properties, being largely controlled by juvenile wood phenonmenon.

As mentioned earlier, no general trend or significant differences were found in average power consumption in the three trial pulps, i.e. when a dry ton of thermomechanical pulp is manufactured either from SM, RC or FT wood. This is well in agreement with Braaten et al. (1994), who manufactured TMP in pilot-scale from Norway spruce. A relatively high proportion of pulp fines material from juvenile type raw material, found also here in FT pulps, is reported by numerous studies made elsewhere (Corson 1983, Richardson et al. 1992, Hatton and Johal 1993, etc.). Above all, perhaps most interesting statements can be done in the area of pulp strength and optical properties. Namely, FT pulp had considerably poorer tear index and somewhat inferior tensile and burst index than the other two pulp types. This was regardless whether the comparison was made at constant freeness or specific energy consumption.

On the other hand, FT pulp light scattering power and brightness was superior to any other pulp. Similar findings is has been found elsewhere, when juvenile wood from various softwoods are subjected to refining (see e.g. Corson 1983, Hatton and Cook 1991, Braaten 1994). High light scattering coefficent seems to be the most characteristic and exclusive property, found in mechanical pulps made from juvenile wood. Interestingly, mechanical pulp from juvenile wood tend to give better optical properties than corresponding pulp from mature wood sources, when comparison is made at constant fines content. Therefore, good light scattering seems to result from the quality of fines material. Moreover, it should be noted that FT pulp were inferior in light absorption properties due to its high lignin content, compared with the other pulps (Table 24). However, due to their very high scattering coefficents, FT pulps gave systematically better brightness.

Contrary to what could have been expected from pulp particle size distributions, the obtained sheet structural properties did not deviate significantly between the three pulp types. It has been reported that mechanical pulp sheets made from juvenile fiber would give good sheet density, smaller bulk, and better surface properties in terms of porosity and smootheness (Kibblewhite 1981, Harris 1993). No such trend was observed here. Moreover, no practical differences in these properties between SM, RC, and FT pulps were noticed, neither at constant SEC or freeness-level. This refers to the fact that the mechanisms being involved in sheet consolidation and structure are rather complicated, being not primarily determined by type fiber raw material. It should be pointed out that no paper machine trials were carried out in order to test the sheet consolidation in the final end-product.

Extractives

The effects of extractives in TMP pulp manufacture and subsequent paper making was discussed thoroughly in the theoretical study (Section 2.10.2). It was concluded that the importance of extractives in the manufacture of pulp is greater than what would be expected on the basis of their proportion of the raw material. The main practical effects caused by wood extractives were "pitch" contamination in pulp and paper making equipment, occasional sheet breaks, paper dirt specks, loss of brightness potential and the effluent toxicdity. Most of these harmful effects can be attributed to resin acids found in wood extractives.

It should be noted here, that the final extractives content in spruce end-use pulp was controlled mainly by the process conditions, and only to a minor extent by the wood raw-material. With respect to that, it was already stated that the accessibility of extractives in thermomechanical pulping can depend on the type of wood used. In wood, the extractives are present in freely available resin canals as well as in enclosed parenchymatic cells. In TMP manufacture, and in pure mechanical pulping processes, accessible extractives components will be mechanically dispersed during refining. Some of them will stay in dispersion and be washed out, whereas others will either never come out from the solid phase or will agglomerate quickly and precipitate on the fibers and shives (Annergren and Hägglund 1979, Hartler 1985). It has also been shown that unlike in chemical pulping, a large part of the parenchyma cells will break during mechanical pulping, and thus being accessible (Allen 1975). However, the methodology used in this study did not allow to evaluate why SM, RC, and FT raw materials responded in a different manner to refining with respect to their extractives content. Moreover, wood growing season and the storage of wood among other factors affect the initial content in chips, thus these results may not have good reproducability.

As a whole, however, it can be suggested that due to relatively low extractives content in each pulp, no major pulp brightness or strength loss has occurred. Since pure mechanical pulps, such as TMP, are the main input sources of extragenous material in paper manufacture, these effects are briefly discussed here. Namely, despite its significantly higher original extractives content in first-thinnings wood, the FT newsgrade end-use pulp contained only about 4 kg DCM extractives per ton of dry pulp, whereas that for SM pulp was double, about 8 kg in a ton of pulp (see Fig. 74). The corresponding amount for OG pulp is approximately 6 kg. This means that in TMP mill operation rate of 500 ton/d, newsgrade pulp from SM wood brings daily 2000 kg more "pitch" generating material into paper machine white water system, than would FT pulp. On the contrary, amount of toxic effluents from FT on TMP manufacture are much higher than from other woods.

3.5.2 Newsgrade Pulps from SM, RC and FT Wood

The obtained results indicated significant differences between the three trial pulps in some key pulp quality variables. Most of this deviation can be easily explained with the determined differences in the wood characteristics of the used raw materials. Since the standard deviation in single pulp properties, such as tear strength, tensile strength, brightness and light scattering coefficent, was smaller than deviation between the obtained average values in SM, RC and FT pulps, it is assumed that sorting the wood for these three categories can considerably reduce variation that normally occurs. For instance, Braaten et al. (1993) showed, in their laboratory scale study of Norway spruce TMP, that variation in such properties than tear strength and light scattering are reduced approximately 20–50 % when topwood, thinnings, slabwood and butt/middle log assortments were refined separately. It is true, though, that a statistically significant difference in average values of some single pulp property between pulps derived from specific wood is of little importance, unless it cannot be operationalized in practice. Firstly, this means that there must be a feasibility to deliver appropriate wood at a right moment into a specific process that is tuned accordingly. Unfortunately, in the present day wood harvesting and pulping systems is this requirement fulfilled only rarely, if at all. Secondly, the identified differences, of commercial importance, in wood assortment's potential to produce more uniform TMP for newsprint or TMP with special properties, must be commercialized in terms of product quality or cost efficiency improvement, which, in turn usually leads to better market performance in a long term. A such example would be an overall reduction of the required amount of reinforcement chemical pulp, or generally improved newsprint quality due to increased pulp quality. Unfortunately, an improvement in some important pulp property can mean a simultaneous deterioration in some other key property, in pulps obtained in this way.

Although the properties of resulting end-product, i.e. newsprint, were not determined here for the reasons mentioned earlier in this study (Section 3.1), the properties of mechanical pulp component in the furnish are known influence more or less in a similar manner on the newsprint quality and manufacture, as on laboratory sheets. For instance, Mohlin and Wennberg (1983) has shown that due to fundamental differences between mechanical and chemical pulp particles, they form rather separate structures or networks in a paper sheet. Therefore, the main influences of the used TMP, being the main component in the furnish, are expected to transmitted via its strength and optical properties. Moreover, the surface and sheet properties of the network which are formed during paper manufacture is at least to some extent affected by the properties of particles present in mechanical pulps. The observed differences and patterns in the fiber and particle properties, strength properties, optical properties and sheet structure, between SM, RC and FT end-use pulps, and their relevance for fulfilling various requirements of newsprint furnish are discussed in the following text.

Pulp Fiber and Particle Properties

With respect to initial wood characteristics, the most obvious and pronounced differences in pulp fiber and particle properties, between SM, RC and FT pulps, were found in proportions of Bauer-McNett fractions, and average fiber dimensions. However, the differences of this magnitude found either in the long fiber content (R28), fines content (P200), fiber coarseness and cross-sectional dimensions of the long fibers (R14, 14/28), average fiber length and its distribution, and shives content, irrespective to the level of freeness or specific energy consumption, well explain the obtained pulp quality from each raw material type. However, due to many interrelated wood properties, as well as pulp properties, and numerous mechanisms involved for instance in the pulp strength, it is impossible to attribute the found differences to any single wood properties. Instead, the type of wood – SM, RC, and FT wood – via obtained pulp fiber and particle properties have good correlation with the quality of pulp manufactured in similar conditions. Nevertheless, despite dramatical differences in the average coarseness and size of individual TMP fibers, and irrespective to pulp strength and optical properties, there were practically no differences in the sheet structural and surface properties, unlike assumed in hypothesis 5. Thus, these properties are determined by other factors.

During the refining, it came out quite clear that it was not possible to refine FT pulp any further, that is, from 88 ml to a lower freeness, fullfilling the company minimum process specifications (target value 75 ml, as shown in Table 21). Otherwise considerably more FT fibers would have been cut resulting even poorer strength properties, not to mention the elevated energy consumption while doing so. However, it is likely that company TMP production specifications are formulated using the average wood raw-material flow as a base, and not according to any extreme wood type, such as thinnings. Therefore, it was very much understandable that all of these requirements, in terms of final pulp freeness, strength properties and shives content, were easily obtained with the use of RC wood. Wood from old-growth regeneration cuttings represents the greatest obtainable variation in wood properties, and well reflects the variation in normal wood quality.

Strength Properties and Sheet Structure

It was shown that both tear and tensile strength in pulps were largely controlled by the long fibers, that is, their proportion and average fiber length. No dramatical differences were found in pulp bonding properties, in terms of sheet apparent density or the quality of either long fiber, middle or fines fractions in pulps (Table 24) when determined at constant freeness or SEC. Actually, SM end-use pulp showed somewhat better fiber external fibrillation than other pulps. Correspondingly, middle fractions of RC pulp had the best bonding properties. There was insufficient data to determine the influence of each pulp particle fraction on final pulp quality. However, considering all data collected from sheet physical and structural properties, there is no indication that, for instance, thinner cell walls of FT pulp fibers would have affected the degree of fiber development in terms of their flexibility, collapsiability, and fibrillation of these fibers, and corresponding contribution to the overall bonding and subsequent improvements in strength properties. Data from the sheet cross-sections shows that there are uncollapsed thick-walled fibers in all pulps, not only in SM and RC sheets (Appendix 11).

Since the apparent sheet density is a relative measure of pulp bonding properties and sheet consolidation, it is interesting to view tear and tensile indexes related to this property. This is shown in the following figures (Figs. 75 and 76).

It is shown above that the sheet apparent density does not change the order of the pulps in terms of their tear strength, and only to a minor extent that in terms of tensile index. FT pulp remained the still the poorest in this respect.

As mentioned earlier in this section, despite the dramatically deviating particle morphology between all of the three pulps (SM, RC, and FT), no considerable differences were found either in sheet apparent density, bulk, porosity or surface smoothness. In other words, quite uniform sheet structure and surface can be produced from all spruce wood assortments, with a special reference to their printing properties. This critical examination does not include the effect of pulp optical properties on printing. However, obtained optical properties will be discussed in the following paragraph. Moreover, one distinction between the three pulp types, at least in theory, could be the better obtainable sheet formation using FT pulp on the papermachine (Jonsson 1979) due to its considerably smaller fibers, if compared to other pulps. This fact could bring some advantages in paper manufacture in certain conditions.

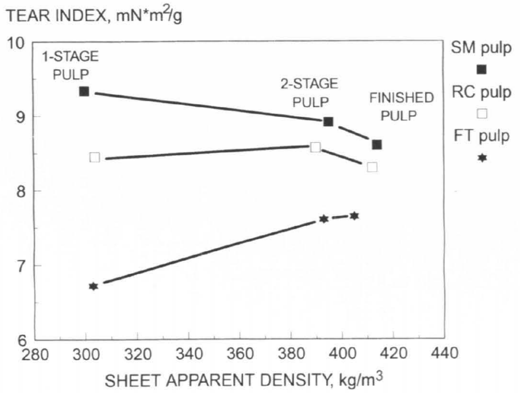


Figure 75. Tear index vs. sheet apparent density of the 1-stage (Line A), 2-stage (Line A), and newsgrade end-use thermomechanical pulps (all lines and reject refining) made from sawmill chips (SM), regeneration cuttings wood (RC), and first-thinnings wood (FT). Data points on the left are from primary refiners, whereas those on the right are from end-use pulps.

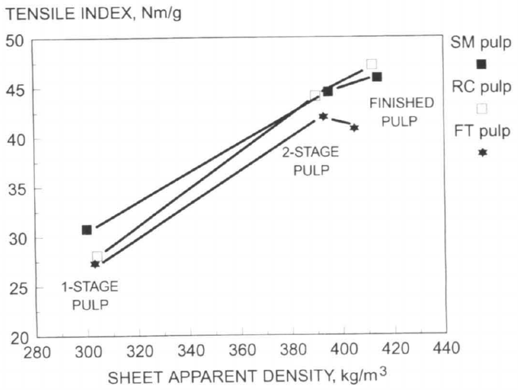


Figure 76. Tensile index vs. sheet apparent density of the 1-stage (Line A), 2-stage (Line A), and newsgrade end-use thermomechanical pulps (all lines and reject refining) made from sawmill chips (SM), regeneration cuttings wood (RC), and first-thinnings wood (FT). Data points on the left are from primary refiners, whereas those on the right are from end-use pulps.

Optical Properties

According to Saltin and Strand (1992) for the unbleached TMP brightness is the dominating factor affecting newsprint brightness on the paper machine. Moreover, they found that refining conditions had no effect on the unbleached pulp brightness, and concluded the unbleached pulp brightness is largely determined by the initial chip brightness and wood properties. In this study, too, it was shown that pulp optical properties, in terms of brightness and light scattering coefficent, were sovereignly determined by wood type. Only the sheet opacity, except in the early stages of refining, was not determined by wood type, but mainly by applied refining energy. In fact, no differences were found in opacity values of either 2-stage or end-use pulps, at constant SEC or freeness. However, pulp light scattering coefficent is the most reliable and independent optical property indicating mechanical pulp's optical performance in various paper end-products. Superior light scattering properties in FT pulps can be attributed to the quantity and quality of fines material as well as the juvenile type of fibers in pulp.

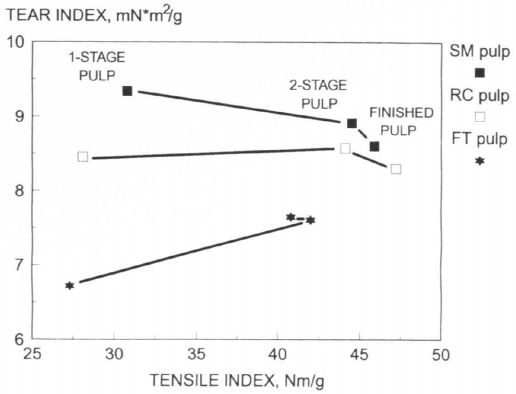


Figure 77. Tear index vs tensile index of the 1-stage (Line A), 2-stage (Line A), and newsgrade end-use thermomechanical pulps (all lines and reject refining) made from sawmill chips (SM), regeneration cuttings wood (RC), and first-thinnings wood (FT). Data points on the left are from primary refiners, whereas those on the right are from end-use pulps, with the exception of FT pulp, where the middlemost value belongs to end-use pulp.

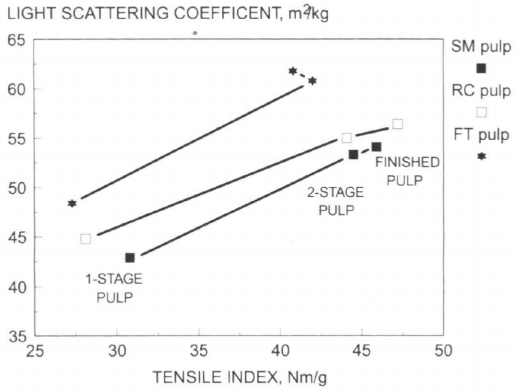


Figure 78. Light scattering coefficent vs tensile index of the 1-stage (Line A), 2-stage (Line A), and newsgrade end-use thermomechanical pulps (all refiner lines and reject refining) made from sawmill chips (SM), regeneration cuttings wood (RC), and first-thinnings wood (FT). Lowest light scattering values in a given pulp are from primary refiners, whereas the highest belongs to end-use pulps.

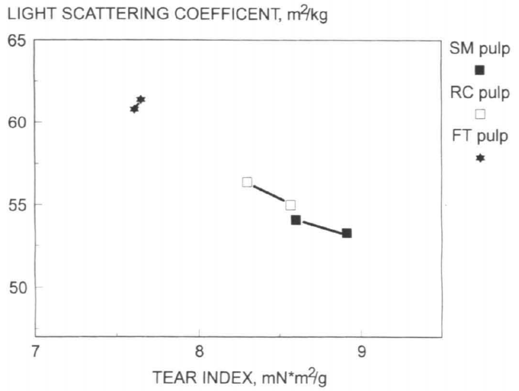


Figure 79. Light scattering coefficent vs tear index of the 2-stage and end-use thermomechanical pulps made from sawmill chips (SM), regeneration cuttings wood (RC), and first-thinnings wood (FT). The highest value in light scattering coefficent in a given pulp is the 2-stage pulp, whereas the lowest belongs to end-use pulps.

Important Pairs of Properties

A commonly used technique to compare and evaluate the paper making potential of different pulps is to consider the critical pairs of properties, i.e. those important properties which develop in opposite directions when a control variable of the furnish changes, and find out experimentally how these change when the furnish composition changes. Optimization of the newsprint furnish performance in such a way is out of the scope of this study. However, the properties of mechanical pulp are highly decisive for the paper properties, especially in the case of newsprint which can be manufactured even from 100 % TMP. Therefore, it is assumed that at least the optical and strength properties of SM, RC, and FT pulps are likely to be transmitted to newsprint to a large extent. In the following figures (Figs. 77–79), three important pulp properties – tear index, tensile index, and light scattering coefficent – of the 1-stage (Line A), 2-stage (Line A) and end-use pulps are plotted as a function of each others. In the case of light scattering vs. tear strength (Fig. 79.), the values from 1-stage refining are not shown. Using these charts a paper maker can easily evaluate the pulps' paper making potential.

Differences between the pulps in terms of plotted optical and strength properties are evident from the Figures 77–79. If optical properties are used as the criteria for evaluation, first-thinnings wood could give superior pulp. This is in the condition that both tear and tensile strength of FT pulp would be sufficent, which seems not to be the case with newsprint (see Table 21). However, pulp from regeneration cuttings wood (RC) would give the best combination in both strength and optical properties. Although being out of the scope of this study, pulp from sawmill chips (SM) would not necessarily be a poor furnish component for newsprint, since it is known that replacing the chemical pulp component by increasing the proportion of TMP even up to 100 %, would contribute the overall newsprint optical and printing properties (Vaarasalo et al. 1981, Weidhaas 1981, Paulapuro and Laamanen 1988). In other words, sufficent newsprint opacity and brightness levels could be still obtained because good strength characteristics of SM pulp would allow a corresponding increase in its relative use. This would simultaneously help to reduce the unit manufacturing cost of newsprint (per ton), too. Furthermore, it should be remembered that there is always a wider space to engineer the end-product properties by mixing different components, than changing the manufacturing conditions, and subsequently the properties, of any pulp. However, in this respect,the SM, RC and FT pulps can be utilized by a paper maker as a different furnish choices for a best mix.

3.6 Conclusions

The important wood and fiber properties of Finland-grown Norway spruce and their expected influence on thermomechanical pulping were already determined in the theoretical study (Chapter 2). Basing on these results, three potentially different Norway spruce pulpwood assortments were defined and selected for the empirical study. In the empirical part of this investigation, the average wood and fiber properties and their variation were determined in sawmill chips (SM), old-growth regeneration cuttings wood (RC) and first-thinnings wood (FT) . Subsequently, each assortment, approximately 4000 m³ of wood chips, were subjected to one-day (24 h) mill-scale thermomechanical refining at constant pulping conditions to compare the obtainable properties of newsgrade pulp. The strength, optical, and fiber and particle properties of TMPs made from these assortments deviated significantly. Most of the differences between pulps can be attributed to certain wood and fiber variables in the raw-materials. The main conclusions of the study can be summarized as follows:

1. Significant differences were found in the wood and fiber properties between the SM, RC, and FT woods. The most important wood properties in terms of TMP quality were the average fiber dimensions and the amount of juvenile fibers, being in line with the theoretical study.
2. No statistically or practically significant differences were found in pulp specific energy consumption. Thus, the obtained results supported Hypothesis 1. However, when wood basic density is taken into account, the RC pulp has the lowest and SM pulp the highest relative production cost.
3. Commercial newsgrade TMP can be produced from all spruce pulpwood assortments alone, except from first-thinnings (FT), which does not fulfill the strength requirement.
4. SM pulps had the highest tear and tensile strength, while showing poorest brightness and light scattering coefficent values. SM pulps had also the greatest long fiber fraction, of which fibers were longest and largest in size, compared to other pulps. Hypothesis 2 was supported.
5. FT pulps, with poor tear and tensile strength, had superior optical properties in terms of brightness and light scattering properties. Pulp from first-thinnings gave also the highest fines content, but the lowest long fiber content, where the fibers were considerably smaller than in any other pulp. The above was in agreement with Hypothesis 4.
6. RC pulp properties fell always between the SM and FT pulp properties, being closer to SM pulps, though. However, RC pulp had the highest shives content. Thus, Hypothesis 3 was supported.

7. Despite the dramatically different particle size distributions in the three pulp types, no statistically or practically significant differences were found in pulp sheet apparent density, bulk, smoothness, and porosity, thus, contradicting Hypothesis 5.
8. There were no significant interactions between wood assortment and specific energy consumption or freeness level for any of the above key pulp properties. Practically, this means that the difference in pulp properties between two wood assortments are in the same order regardless the level of specific energy consumption or pulp freeness.
9. The variation that normally occurs in wood flow, impairing the overall pulp quality and energy consumption, can be diminished dramatically by refining these more uniform assortments separately. In that case, however, freeness is a poor process control variable.

4 Practical Considerations

Wood Raw Material Segregation

As already has been pointed out earlier, the results of the empirical study apply only to those woods and those pulps in question with a special reference to the trial pulp mill. However, both the determined wood characteristics in SM, RC and FT assortments, and in the derived thermomechanical pulps are consistent with what would have been expected basing on heterogenous literature from softwood properties, as well as from various pulping processes. Therefore, at least some of the obtained results could be used generally for further improving the overall performance of the forest products conversion chain which starts in the forest and ends up to a paper end-user.

It was clearly shown in this study that obtainable pulp properties and quality depend primarily on the type of sprucewood used in TMP manufacture. However, the uneven pulp quality is known to result almost unquestionably from unknown fluctuation in wood raw material properties or processing conditions. Therefore, this investigation has brought some light in the ever-going discussion to which extent of the variation and off-spec quality in pulp and paper products can be attributed to wood variables. Unfortunately, even though the variation in wood quality were known at a given moment, a thermomechanical pulping process or subsequent paper making process can only rarely respond to and off-set this variation.

The above highlights the need for proper wood homogenization by segregating various assortments. Generally, in Norway spruce we have a relatively diverse and valuable wood resource containing a wide range of fiber types which can be segregated before and/or during processing. Thus the various types of fiber can be preselected so that most suitable raw material can be used in the manufacture of high quality paper products. Examples of such raw material segregation in TMP production has already been mentioned in the theoretical study, for instance in Chapter 2.1.4. Mills with integrated kraft pulping facilities may have a further opportunity to upgrade raw material quality for mechanical pulping through chip fractionation (Tyrväinen 1989, Harris 1993).

The two extreme wood assortments by far, in terms of their wood characteristics and potential in TMP, were wood from first-thinnings and sawmill chips. As concluded in the preceding section (Section 3.5), merchantable newsgrade TMP cannot be made from FT wood alone. However, the requirement for sufficent strength properties could be achieved with a minimum addition of stronger pulp such as SM or RC pulp. Such pulp would be superior in its optical properties and a good choice for certain end-uses. Moreover, it was shown in Chapter 3.4.1 that the excellent strength properties of pulp from SM wood could be further enhanced by optimizing the average chip length, which, in turn, would lead to increased average pulp fiber length.

Nevertheless, since the pulping potential of both SM and RC wood assortments are closer to what is normally used as raw material in Scandinavian TMP mills, the most interesting wood category, from the processing and end-product point of a view, is the problematic first-thinnings (FT) wood consisting mainly of juvenile type of fiber. For Norway spruce, its real influence on thermomechanical pulping has not yet been generally recognized (see e.g. Braaten et al. 1993, Brolin et al. 1995). It should be noted that many TMP mills in the Southern U.S., New Zealand and Chile, for instance, are currently receiving preferably their raw-material supply coming almost solely from short-rotation, fast-growing plantation pine, and therefore well adapted 30–100 % juvenile wood contents (Kellison and Hitchings 1985, Harris 1993, Williams 1993). In this case, however, mature wood of *Pinus taeda* or *Pinus radiata* with extremely coarse fibers is not favoured for mechanical pulping.

In Finland, and especially in the area wherefrom wood for EG Varkaus is procured, thinnings wood could never comprise more than a few percents of the natural wood supply (Härmälä, I., personal comm., Sirainen 1995). Another question is though, if first-thinnings wood from other procurement areas is being directed by purpose to Varkaus TMP mill. In normal TMP production, a situation, where mere first-thinnings wood or great amounts of it alone, does not occur very often. For instance, at EG Varkaus TMP mill, a mixture containing at least 50 % of sawmill chips (SM) is being constantly prepared prior to chip preheating. Consequently, when effectively mixed in mill's normal wood supply, even relatively large amounts of thinnings wood should create no problemes in refining or product quality. However, if not mixed effectively or if large amounts thinnings wood arrives as roundwood and is being pulped, say several hours in a roll, problems may arise in terms of acceptable pulp strength properties. The above described situation can be possible due to unexpected disturbances in raw material supply for the refiners.

As has become apparent from the foregoing, wood from conifer thinning operations must be processed and blended in the harvesting and woodyard operations so that the mill can either make use of the juvenile wood properties in certain products, or minimize the impact by blending with mature wood sources (older trees, wood products residuals). What is said in this study from first-thinnings wood (FT) is largely true also with spruce top logs and unmerchantable tops, which contain noteworthy amounts of juvenile wood (Corson 1983, Braaten et al. 1993, Hatton and Johal 1993 etc.). This fact can be naturally taken into consideration, if raw material segregation is practiced for Norway spruce.

Pulp and Paper Making

There are a few ways to maximize the potential of FT wood in thermomechanical pulping and paper products made of it. Firstly, if its negative impacts, mainly on pulp strength properties are to be minimized with the least overall effort, FT chips should be evenly mixed in the raw material mix. It was already mentioned earlier that the total volume of first-thinnings wood arriving the mill is relatively low. Secondly, the production conditions could be optimized for each wood type, which was out of the scope of this study and therefore not done in this trial. Thirdly, if there would be a paper product in terms of special customer requirements where FT pulp alone or in a mixture could be advantageous, this approach should be chosen. As has been discussed earlier, the prerequisite for that is effective wood and fiber segregation which starts from the forest and ends up to a paper.

Mohlin and Wennberg (1984) has shown that the mechanical and chemical components behave independently in wood containing publication papers, so that the contribution of the mechanical pulp depends on its own quality. As all pulps of this study showed different papermaking potential it is generally obvious that the requirements of a special paper product can be more easily met by selecting the most suitable furnish component. This is especially true today, when "tailor-made" products are increasingly manufactured. According to Hooper (1988), every mixture is a compromise, and there is always a trade-off between strength and optical properties. Paper grades where the tear and tensile resistance is mainly attributed to chemical reinforcement pulp and the proportion of mechanical pulp is lower, the use of FT pulp could be favoured. One example belonging to this category is light weight coated paper (LWC). In this low caliber (thickness) paper, the quality effects of finer fiber and superior optical properties of FT pulp would be distinctly advantageous. Moreover, the absence of large diameter, thick-walled latewood fibers in FT pulp is a preferable property for LWC base paper (Harris 1993, Aspler and Beland 1994). In fact, the properties of FT TMP are comparable in many respect to those of stone groundwood (SGW). Therefore, it could be used as a replacement of SGW pulp in certain situations.

It was already intuitively obvious before the pulping trials, that woods with properties deviating this much should not be refined in the same conditions to produce the best possible pulp from each raw material. This is supported also in the literature (deMontmorency 1964, May 1973, Leask 1981, Pearson 1983, Malinen 1986, Harris 1993). However, since the purpose of this study was to investigate the potential of the three different wood assortments (SM, RC, FT), in terms of their pulping properties as TMP raw-materials, no attempt was made to optimize the pulp properties, for example, by applying higher refining energies, or varying production rate or consistency. On the contrary, it was necessary to refine the different spruce pulpwood assortmets of this study in identical process conditions for the sake of experiment. There are basically two principal ways to improve the possibilities of producing ideal mechanical pulp. Namely to develop the fibration process itself and to develop methods for post-treatment (Kurdin 1979, Jackson 1985, Paulapuro and Laamanen 1988). The latter means includes screening, and selective mechanical or chemical treatment of either the long fibers or rejects. Neither of these were optimized in this study, leaving room for significant development with both methods.

Supporting to the above discussion, some interesting findings were obtained during refining. Namely, it has already been stated earlier that it was not possible to refine FT end-use pulp from its final freeness of 88 ml to the target freeness 75 ml, since it would have caused even more severe loss in strength properties. However, about 10 % total savings in energy consumption, could have been reached, if FT pulp would not have been refined any further after 2-stage. This is based on the fact that rejects refining did not bring any dramatical improvements for pulp quality in the case of FT pulp. The shives content and sheet properties, except the tear strength, could still be at an acceptable level. Moreover, higher freeness (118 ml) would allow better paper machine operation. The above suggest that a modified pulping process is required for a fuller utilization of this extreme type of sprucewood in newsprint manufacture.

To obtain better optical and properties in SM pulp, it could have been refined further to a somewhat lower freeness and still have acceptable pulp in terms of strength properties. Since originally SM pulp has the coarsest long fibers and smallest fines fraction, this would possibly enhance the overall sheet structural properties, too. Of course, it would have occured only with elevated energy consumption. Another approach could have been to post-refine the long fibers or coarse rejects separately. It has been emphasized by several investigators, that by treating only the coarsest fraction of the TMP, a furnish with the necessary bonding requirements and optical properties can be produced from a single pulp mill. Furthermore, larger the diameter and thicker the fiber wall in a given wood raw material, the more important is to develop the flexibility of the long fibers with the mechanical and chemical (Jackson and Williams 1979, Hooper 1988, Corson 1991, Harris 1993).

If SM pulp is used as a single mechanical pulp component in newsprint, it should be pointed out that despite the lowest light scattering properties of SM pulp, its considreably higher strength potential allows the increase of its relative share in the furnish, thus replacing the chemical pulp. Consequently, a net gain in light scattering power could be still attained in the final newsprint end-product (Vaarasalo et al. 1981, Weidhaas 1981). If optical or surface properties of SM pulp are not satisfactory for a given paper product, its high strength potential allows to add for instance stone groundwood (SGW), which typically have superior optical properties and printing of any mechanical pulps, as a secondary mechanical pulp component in the furnish.

In reporting significant quality differences in newsgrade thermomechanical pulp, when manufactured separately from three different sprucewood assortments, i.e. sawmill chips (SM), regeneration cuttings (RC) and first-thinnings (FT), obviously both economical and technical influences are involved. This study should now give rise to further studies considering the mechanisms and causes involved. Technical studies should also be welcome in the field of process control and optimization of the whole paper manufacturing process – from woodlands operations to the paper end-product.

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APPENDIX 1.

RESULTS FROM CHIP PARTICLE ANALYSIS (EG Woodhandling Div.):

ENSO PUBLICATION PAPERS / UNIVERSITY OF HELSINKI (Dept. of Forest Resources Mgmt.)

Sawmill chips (EG Varkaus sawmill), spruce. TMP 1. silo, Nov. 4-5, 1993 (through 3 working shifts)

SM WOOD Sample	Dry-matter, %	Moisture, % (MC$_w$)	Bark weight-%	PARTICLE SIZE DISTRIBUTION	(%)	**PRIME**	**CHIPS**		
				+45 mm	45/R8	**R8/13**	**13/7**	7/3	-3 mm
Screening nr. 1	38.10	61.9	0.13	0.4	8.2	**75.4**	**13.7**	1.8	0.2
Screening nr. 2	37.95	62.05	0.28	0.0	9.5	**76.5**	**12.1**	1.8	0.0
Screening nr. 3	38.52	61.48	0.03	0.0	7.1	**76.4**	**14.1**	2.0	0.1
Screening nr. 4	38.97	61.03	0.08	0.3	7.0	**77.0**	**14.0**	1.4	0.0
Screening nr. 5	38.38	61.62	0.05	0.1	9.6	**75.3**	**13.2**	1.4	0 1
Screening nr. 6	38.23	61.77	0.20	0.0	9.5	**75.1**	**13.6**	1.5	0.1
Screening nr. 7	37.60	62.40	0.08	0.4	5.5	**74.4**	**15.7**	3.2	0.4
Screening nr. 8	39.32	60.68	0.10	0.0	6.5	**77.5**	**13.2**	2.3	0.2
Screening nr. 9	38.39	61.61	0.20	0.0	9.2	**74.3**	**14.3**	1.0	0.1
Screening nr. 10	38.24	61.76	0.0	0.4	9.2	**73.1**	**15.3**	1.7	0.1
Screening nr. 11	37.47	62.53	0.0	0.0	7.5	**75.5**	**13.9**	2.4	0.3
Screening nr. 12	38.48	61.52	0.10	0.2	6.5	**70.0**	**17.8**	4.7	0.6
Average:	38,30	61.70	0.10	0.15	7.94	75.04	14.24	2.10	0.18
(Stand.dev.)	(0.516)	(0.510)	(0.09)	(0.178)	(1.44)	(2.009)	(1.464)	(1.00)	(0.175)

Average chip length: 18.13 mm (s.d. 2.84 mm), Approximate average chip thickness: 4.25 mm (s.d. 1.26 mm)

Chips from regeneration cuttings (E-G. Varkaus Wood Procurement District), spruce. TMP 2. silo, Nov. 18-19, 1993 (through 3 working shifts).

RC WOOD Sample	Dry-matter, %	Moisture, % (MC$_w$)	Bark weight-%	PARTICLE SIZE DISTRIBUTION	(%)	**PRIME**	**CHIPS**		
				+45 mm	45/R8	**R8/13**	**13/7**	7/3	-3 mm
Screening nr. 1	50.82	49.18	0	0.1	3.1	**64.3**	**27.2**	4.8	0.1
Screening nr. 2	47.95	50.05	0	0.6	1.9	**63.4**	**28.2**	5.4	0.2
Screening nr. 3	50.86	49.14	0	0.3	2.6	**61.3**	**29.7**	5.7	0.2
Screening nr. 4	50.12	49.88	0	0.2	3.1	**61.9**	**28.5**	5.8	0.2
Screening nr. 5	51.08	48.92	0	0.2	3.2	**63.1**	**27.6**	5.7	0.0
Screening nr. 6	49.84	50.16	0	0.1	3.5	**60.7**	**28.7**	6.4	0.3
Screening nr. 7	50.98	49.02	0	0.0	1.1	**54.8**	**31.8**	11.4	0.6
Screening nr. 8	50.83	49.17	0	0.0	1.6	**54.9**	**31.4**	11.0	0.8
Screening nr. 9	49.79	50.21	0	0.0	1.7	**62.2**	**30.0**	5.7	0.2
Screening nr. 10	48.85	51.15	0	0.5	1.2	**58.1**	**32.2**	7.4	0.3
Average:	50.40	49.6	0	0.2	2.3	60.47	29.53	6.43	0.29
(Stand. dev.):	(0.719)	(0.720)	0	(0.18)	(0.90)	(3.411)	(1.786)	2.351	(0.238)

Average chip length: 17.76 mm (s.d. 2.41 mm), Approximate average chip thickness: 3.99 mm (s.d. 1.01 mm)

Chips from first-thinnings (E-G. Varkaus Wood Procurement District), spruce. TMP 2. silo, Dec. 15-16, 1993 (through 3 working shifts).

FT WOOD Sample	Dry-matter, %	Moisture, % (MC$_w$)	Bark weight-%	PARTICLE SIZE DISTRIBUTION	(%)	**PRIME**	**CHIPS**		
				+45 mm	45/R8	**R8/13**	**13/7**	7/3	-3 mm
Screening nr. 1	42.42	57.58	0	0.2	5.9	**66.1**	**22.8**	4.5	0.1
Screening nr. 2	41.31	58.69	0	0.3	6.9	**65.3**	**22.2**	4.9	0.1
Screening nr. 3	41.44	58.56	0	0.1	10.2	**64.4**	**20.3**	4.7	0
Screening nr. 4	41.21	58.79	0	0.4	7.2	**65.1**	**22.0**	5.2	0.1
Screening nr. 5	40.82	59.18	0	0.4	7.3	**65.4**	**21.6**	5.0	0.1
Screening nr. 6	40.02	59.98	0	0	5.5	**67.8**	**21.8**	4.6	0.1
Screening nr. 7	40.89	59.11	0	0.7	3.5	**57.4**	**29.9**	8.2	0.2
Screening nr. 8	40.72	59.28	0	0.4	6.9	**65.1**	**21.8**	4.8	0.1
Screening nr. 9	39.40	60.60	0	0.6	3.0	**59.1**	**29.6**	7.2	0.2
Screening nr. 10	40.32	59.68	0	0.4	4.3	**62.4**	**26.6**	5.0	0.1
Average:	40.86	59.15	0	0.35	6.07	63.89	23.86	5.41	0.11
(Stand. dev.):	(0.833)	(.833)?	(0)	(0.212)	(2.13)	(3.246)	(3.51)	(1.25)	(0.057)

Average chip length: 15.84 mm (s.d. 3.16 mm), Approximate average chip thickness: 3.86 mm (s.d. 1.28 mm)

APPENDIX 2

AVERAGE CHIP PROPERTIES OF SM, RC, AND FT WOOD RAW-MATERIALS

Chip property	**Wood type** **Saw mill residual wood chips (SM)**	**Regeneration cuttings wood chips (RC)**	**First-thinnings wood chips (FT)**
Chip size distribution			
> 45 mm (overlength), %	0.15	0.20	0.2
45/R28 (overthick), %	7.94	2.30	5.9
R8/13 (accepts), %	75.04	60.47	66.1
13/7 (accepts), %	14.24	29.53	22.8
7/3 (pin chips), %	2.10	6.43	4.5
< 3 mm (fines), %	0.18	0.26	0.1
Thickness, mm	4.25	3.99	3.86
Length, mm	18.1	17.7	15.8
Bark content (by weight), %	0.1	0	0
Moisture content, %	61.7	49.6	59.2

APPENDIX 3. LIST OF STANDARD METHODS USED

Hot disintegration,	SCAN-M10:77
Dry matter content (%),	SCAN-C3:78
Freeness (ml),	SCAN-M4:65
Somerville shives (%)	TAPPI R304
Pulp sheets	SCAN-M5:76
Basis weight (g/m2)	SCAN-M8:76
Density (kg/m3)	SCAN-P7:75
Bulk (m3/kg)	SCAN-M8:76
Tensile index (Nm/g)	SCAN-P38:80
Tensile stretch, (%)	SCAN-P38:80
Modulus of elasticity, N/mm2	SCAN-P38:80
Murtotyöindeksi (J/g)	SCAN-P38:80
Tear index (mNm2/g)	SCAN-M8:76
Burst index (kPam2/g)	SCAN-M8:76
Air resistance, Bendtsen (ml/min)	SCAN-P60:87
Roughness, Bendtsen (ml/min)	SCAN-P21:67
ISO-Brightness (%)	SCAN-P3:75
Light scattering coefficent (m2/kg)	SCAN-C27:76
Light absorption coefficent (m2/kg)	SCAN-C27:76
Opacity (%)	SCAN-P8:75
Y-value, %	SCAN-P8:75
DCM extractives (%)	SCAN-C7:62
Chip laboratory screening	SCAN-CM 40:88
Chip dimensions	SCAN-CM 40:88
Chip bark content	SCAN-CM 40:88

APPENDIX 4.

RESULTS OF MILL-SCALE TMP MANUFACTURE.

Average properties of I-stage, II-stage and newsgrade end-use thermomechanical pulps manufactured from Norway spruce sawmill residual chips (SM-wood).

Pulp property	Pulp type		
	1st-stage (line A1) TMP	2nd-stage (line A2) TMP	End-use (lines A,B,C) TMP
Pulp energy consumption, kWh/t	1066	1806	2049
CSF Freeness, ml	404	108	80
Consistency (discharge), %	37.1	30.5	10.5
FIBER AND PARTICLE PROPERTIES			
Average fiber length (whole pulp), mm	1.97	1.80	1.72
Average fiber length (14/28 mesh), mm	2.48	2.41	2,40
Bauer McNett-fractions:			
+28 mesh, %	53.1	43.6	40.1
+48 mesh, %	15.4	16.8	16.6
+100 mesh, %	7.2	9.0	9.3
+200 mesh, %	4.7	7.0	7.3
-200 mesh, %	19.7	23.7	26.8
Shives content (Somerville), %	3.28	0.35	0.14
Shives number (PQM), no/g	4571	1780	1272
Fiber coarseness(14/28 mesh), mg/m	0.434	0.351	0.341
Fiber diameter (+14 mesh), µm	NA	NA	34.1
Fiber wall thickness (+14 mesh), µm	NA	NA	3.1
Latewood fibers by w. (+14 mesh), %	24.8	20.9	23.6
Latewood fibers by w. (14/28 mesh), %	20.5	15.6	14.4
Fibrillation index, %	NA	NA	60
Specific filtration resistance (48/200 mesh), m/kg	95	212	236
Specific sedimentation volume (-200 mesh), dm^3/kg	NA	496	513
SHEET PROPERTIES:			
Sheet apparent density, kg/m^3	300	395	414
Bulk, m3/kg	3.33	2.53	2.42
Air resistance(Bendtsen), ml/min	1860	190	120
Roughness (Bendtsen), ml/min	1810	360	270
STRENGTH PROPERTIES:			
Tear index, mN·m^2/g	9.34	8.91	8.60
Burst index, kPa·m^2/g	1.54	2.91	3.09
Tensile index, N·m/g	30.8	44.5	45.9
Tensile stretch, %	1.9	3.0	3.1
Optical properties:			
ISO Brightness, %	56.3	57.9	58.2
Light scattering coefficent, m^2/kg	42.9	53.3	54.1
Opacity, %	92.9	95.8	96.6
Other pulp properties:			
Extractives content (DKM), %	NA	NA	0.83

APPENDIX 5.

RESULTS OF MILL-SCALE TMP MANUFACTURE.

Average properties of I-stage, II-stage and newsgrade end-use thermomechanical pulps manufactured from Norway spruce regeneration cuttings (RC-wood) forest stands.

Pulp property	Pulp type		
	1st-stage (line A1) TMP	2nd-stage (line A2) TMP	End-use (lines A,B,C) TMP
Pulp energy consumption, kWh/t	1063	1783	2036
CSF Freeness, ml	389	112	74
Consistency (discharge), %	39.4	32.5	9.4
FIBER AND PARTICLE PROPERTIES			
Average fiber length (whole pulp), mm	1.86	1.71	1.63
Average fiber length (14/28 mesh), mm	2.14	2.09	2,04
Bauer McNett-fractions:			
+28 mesh, %	51.9	41.8	37.6
+48 mesh, %	17.2	18.1	17.7
+100 mesh, %	8.1	9.6	10.1
+200 mesh, %	4.8	6.8	7.5
-200 mesh, %	18.8	23.7	27.0
Shives content (Somerville), %	3.31	0.39	0.21
Shives number (PQM), no/g	4883	2091	1407
Fiber coarseness(14/28 mesh), mg/m	0.410	0.301	0.278
Fiber diameter (+14 mesh), µm	NA	NA	29.4
Fiber wall thickness (+14 mesh), µm	NA	NA	2.6
Latewood fibers by w. (+14 mesh), %	22.2	19.6	20.9
Latewood fibers by w. (14/28 mesh), %	15.6	12.9	12.9
Fibrillation index, %	NA	NA	44
Specific filtration resistance (48/200 mesh), m/kg	103	275	313
Specific sedimentation volume (-200 mesh), dm^3/kg	NA	513	526
SHEET PROPERTIES:			
Sheet apparent density, kg/m^3	304	390	412
Bulk, m3/kg	3.29	2.56	2.43
Air resistance(Bendtsen), ml/min	1940	250	130
Roughness (Bendtsen), ml/min	1860	440	230
STRENGTH PROPERTIES:			
Tear index, mN·m^2/g	8.45	8.57	8.30
Burst index, kPa·m^2/g	1.36	2.95	3.18
Tensile index, N·m/g	28.1	44.1	47.2
Tensile stretch, %	2.1	3.4	3.8
Optical properties:			
ISO Brightness, %	57.3	58.7	59.7
Light scattering coefficent, m^2/kg	44.8	55.0	56.4
Opacity, %	94.0	95.8	96.2
Other pulp properties:			
Extractives content (DKM), %	NA	NA	0.57

APPENDIX 6.

RESULTS OF MILL-SCALE TMP MANUFACTURE.

Average properties of I-stage, II-stage and newsgrade end-use thermomechanical pulps manufactured from Norway spruce first-thinnings stands (FT-wood).

Pulp property	Pulp type		
	1st-stage (line A1) TMP	2nd-stage (line A2) TMP	End-use (lines A,B,C) TMP
Pulp energy consumption, kWh/t	1010	1767	1954
CSF Freeness, ml	384	118	88
Consistency (discharge), %	38.9	32.1	10.0
FIBER AND PARTICLE PROPERTIES			
Average fiber length (whole pulp), mm	1.64	1.45	1.32
Average fiber length (14/28 mesh), mm	2.09	2.01	2,00
Bauer McNett-fractions:			
+28 mesh, %	42.9	30.8	29.5
+48 mesh, %	21.6	22.4	21.6
+100 mesh, %	9.5	11.2	11.4
+200 mesh, %	4.9	6.8	7.5
-200 mesh, %	21.2	28.8	30.0
Shives content (Somerville), %	2.75	0.16	0.10
Shives number (PQM), no/g	4613	1367	1138
Fiber coarseness(14/28 mesh), mg/m	0.349	0.238	0.221
Fiber diameter (+14 mesh), µm	NA	NA	24.3
Fiber wall thickness (+14 mesh), µm	NA	NA	2.0
Latewood fibers by w. (+14 mesh), %	7.3	8.7	10.1
Latewood fibers by w. (14/28 mesh), %	7.3	7.3	5.9
Fibrillation index, %	NA	NA	44
Specific filtration resistance (48/200 mesh), m/kg	58	151	152
Specific sedimentation volume (-200 mesh), dm^3/kg	NA	485	501
SHEET PROPERTIES:			
Sheet apparent density, kg/m^3	303	393	405
Bulk, m3/kg	3.30	2.55	2.47
Air resistance(Bendtsen), ml/min	1710	270	170
Roughness (Bendtsen), ml/min	1690	310	260
STRENGTH PROPERTIES:			
Tear index, mN·m^2/g	6.72	7.61	7.65
Burst index, kPa·m^2/g	1.22	2.72	2.80
Tensile index, N·m/g	27.3	42.0	40.8
Tensile stretch, %	2.1	3.3	3.4
Optical properties:			
ISO Brightness, %	62.0	62.9	63.2
Light scattering coefficent, m^2/kg	48.4	60.8	61.4
Opacity, %	94.3	95.3	96.1
Other pulp properties:			
Extractives content (DKM), %	NA	NA	0.43

APPENDIX 7.

RESULTS OF MILL-SCALE TMP MANUFACTURE.

Average properties of line A (control refiners) 2-stage thermomechanical pulps manufactured from different spruce wood assortments. Samples are taken after screening.
All values are interpolated to a constant freeness (CSF) 120 ml.

Pulp property	Pulp type		
	TMP from saw mill chips	TMP from regeneration cuttings	TMP from first-thinnings
CSF Freeness, ml	120	120	120
Pulp energy consumption, MWh/t	1780	1772	1765
Consistency (discharge), %	30.9	32.6	32.2
FIBER AND PARTICLE PROPERTIES			
Average fiber length, mm	1.81	1.72	1.46
Bauer McNett-fractions:			
+28 mesh, %	44.1	42.1	31.0
+48 mesh, %	16.7	18.0	22.3
+100 mesh, %	8.9	9.5	11.1
+200 mesh, %	6.9	6.7	6.8
-200 mesh, %	23.5	23.6	28.7
Shives content (Somerville), %	0.43	0.50	0.18
Shives number (PQM), no/g	1820	2170	1386
Fiber coarseness(14/28 mesh), mg/m	0.390	0.305	0.240
Fiber diameter (+14 mesh), µm	NA	NA	NA
Latewood fibers by w. (+14 mesh)	21.0	19.7	8.7
Latewood fibers by w. (14/28 mesh)	15.7	13.0	7.3
Fibrillation index, %	NA	NA	NA
Specific filtration resistance (48/200 mesh), m/kg	207	270	150
Specific sedimentation volume (-200 mesh), dm^3/kg	NA	NA	NA
SHEET PROPERTIES:			
Sheet apparent density, kg/m^3	391	386	392
Bulk, m3/kg	2.61	2.63	2.58
Air resistance(Bendtsen), ml/min	420	460	315
Roughness (Bendtsen), ml/min	235	290	275
STRENGTH PROPERTIES:			
Tear index, mN·m^2/g	9.03	8.54	7.60
Burst index, kPa·m^2/g	2.86	2.88	2.71
Tensile index, N·m/g	44.1	43.8	41.9
Tensile stretch, %	3.0	3.4	3.3
Optical properties:			
ISO Brightness, %	57.8	58.8	62.9
Light scattering coefficent, m^2/kg	53.2	54.9	60.7
Opacity, %	95.7	95.8	95.3
Other pulp properties:			
Extractives content (DKM), %	NA	NA	NA

APPENDIX 8.

RESULTS FROM PULP QUALITY MONITOR (PQM) TESTS.

Average shives characteristics of I-stage, II-stage and newsgrade end-use thermomechanical pulps manufactured from Norway spruce sawmill chips (SM), regeneration cuttings (RC) and first-thinnings (FT).

PQM-classification		A1-stage	A2-stage	End-use TMP
SM PULPS	CSF, ml	404	108	80
Fiber fractions	Fine, %	14.9	28.7	36.2
	Middle, %	31.9	31.4	28.8
	Long, %	53.3	39.9	35
	Length, mm	1.97	1.54	1.37
Shives	Sum, no/g	4571	1780	1272
	Wide, no/g	844	162	109
	Long, no/g	1396	281	165
	Coarse, no/g	76	4	1
RC PULPS	CSF, ml	389	112	74
Fiber fractions	Fine, %	17.1	30.4	37.5
	Middle, %	31.8	32.3	30
	Long, %	50.4	37.3	32.5
	Length, mm	1.88	1.46	1.29
Shives	Sum, no/g	4883	2091	1407
	Wide, no/g	907	216	133
	Long, no/g	1494	342	171
	Coarse, no/g	86	6	3
FT PULPS	CSF, ml	384	118	88
Fiber fractions	Fine, %	23.1	37.7	40.4
	Middle, %	34.4	34.5	32.8
	Long, %	42.5	28.4	26.8
	Length, mm	1.64	1.19	1.13
Shives	Sum, no/g	4613	1367	1138
	Wide, no/g	860	115	98
	Long, no/g	1404	190	124
	Coarse, no/g	52	2	1

APPENDIX 9.

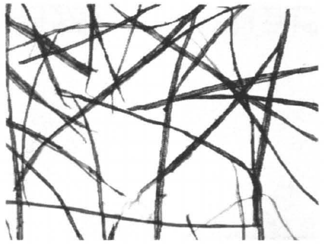
LIGHT MICROGRAPHS FROM TMP FIBERS

Single TMP fibers in the Bauer-McNett 14/28 fractions of the 1-stage , 2-stage and end-use pulps made from different type of sprucewood. Corresponding specific energy consumprion levels and freeness (CSF) values are shown in parentheses. Note a high content of small-sized juvenile wood fibers in FT pulps. 50x magnification used in all light micrographs.

a) 1-stage SM-pulp (1066 kWh/t, 404 ml)

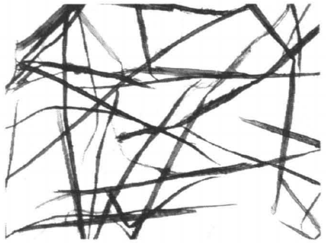
b) 2-stage SM-pulp (1806 kWh/t, 108 ml)

c) Newsgrade end-use SM-pulp (2049 kWh/t, 80 ml)



d) 1-stage RC-pulp (1063 kWh/t, 389 ml)

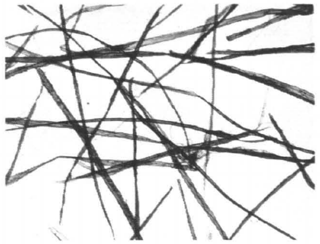
e) 2-stage RC-pulp (1783 kWh/t, 112 ml)



f) Newsgrade end-use RC-pulp (2036 kWh/t, 74 ml)

g) 1-stage FT-pulp (1010 kWh/t, 384 ml)

h) 2-stage FT-pulp (1767 kWh/t, 118 ml)

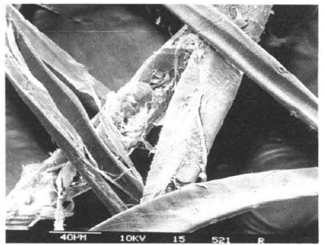


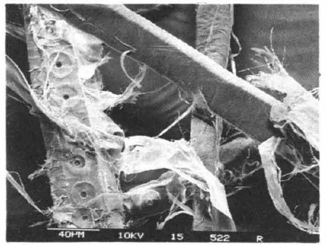
i) Newsgrade end-use FT-pulp (1954 kWh/t, 88 ml)

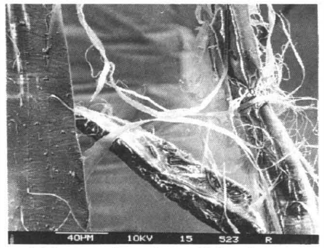
APPENDIX 10.

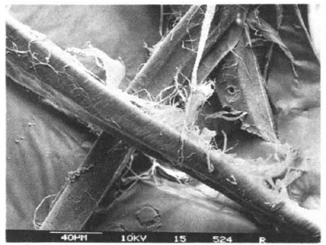
SEM MICROGRAPHS FROM TMP FIBERS.

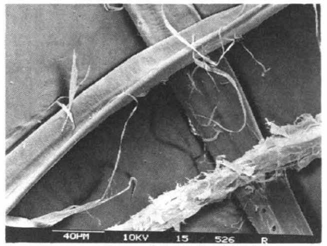
Scanning electron (SEM) micrographs taken from single fibers in the Bauer-McNett 14/28 fractions of the 1-stage , 2-stage and end-use pulps made from different type of sprucewood. Corresponding specific energy consumption levels and freeness (CSF) values are shown in parentheses. Increasing external fibrillation along with increased applied refining energy is clearly visible. Note the nature of fiber surface development: external fibrillation is typical for TMP long fibers, showing mainly the delamination of tracheids and ribbon-like fibrils. Tracheid pits have mainly remained intact. Used magnification: 500x.

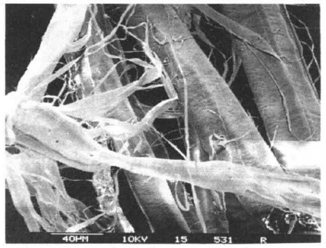

a) 1-stage SM-pulp (1066 kWh/t, 404 ml)

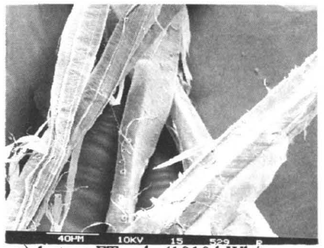

b) 2-stage SM-pulp (1806 kWh/t, 108 ml)

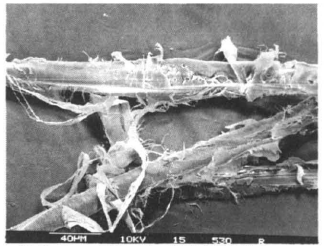

c) Newsgrade end-use SM-pulp (2049 kWh/t, 80 ml)

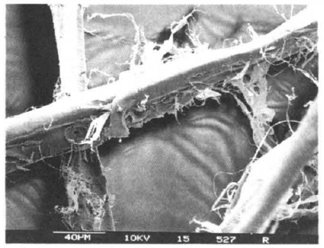

d) 1-stage RC-pulp (1063 kWh/t, 389 ml)


e) 2-stage RC-pulp (1783 kWh/t, 112 ml)


f) Newsgrade end-use RC-pulp (2036 kWh/t, 74 ml)


g) 1-stage FT-pulp (1010 kWh/t, 384 ml)

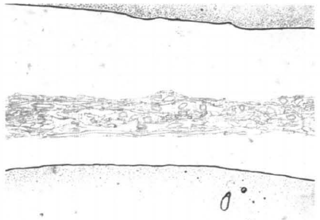

h) 2-stage FT-pulp (1767 kWh/t, 118 ml)

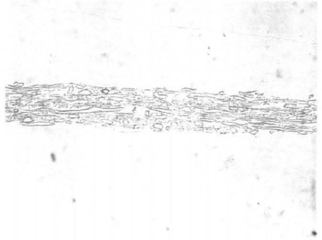

i) Newsgrade end-use FT-pulp (1954 kWh/t, 88 ml)

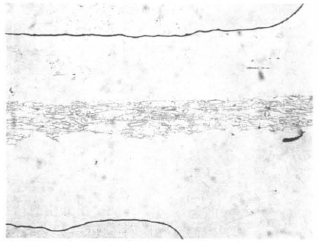
APPENDIX 11.

LIGHT MICROGRAPHS FROM TMP SHEET CROSS-SECTIONS.

Cross-section of sheets prepared from end-use pulp originating from different type of sprucewood. Corresponding specific energy consumption levels and freeness (CSF) values are shown in parentheses. Note a great number of uncollapsed fibers in SM pulp, and to a smaller extent in RC pulp. These fibers are mainly thickwalled latewood fibers. Differences in fiber cross-section dimensions are obvious between the two extremes, SM and FT pulps. Used magnification in the light micrograph: 100x.


a) Newsgrade end-use SM-pulp (2049 kWh/t, 80 ml)


b) Newsgrade end-use RC-pulp (2036 kWh/t, 74 ml)


c) Newsgrade end-use FT-pulp (1954 kWh/t, 88 ml)

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