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MASTER'S THESIS

Establishing a Model for the Dry Density of Heartwood of Norway spruce by Parameters Industrially Measurable on Green Logs

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Preface

This study constitutes the final examination of the Master of Science programme in Wood engineering, as well as the beginning of my Ph D studies. Measurements, literature studies and data analysis have been performed during the year 2004.

Modelling is a creative and dynamic way of doing research. If a good validation data is available the feed-back from a model is instant and new questions are immediately asked; Can the result improve? What is the reason for a model to work? Which are the mechanisms? Although the report is finished, the modelling will continue.

Many people have been contributing to the result presented here. I would especially like to mention Jouko Silén, my referee at Stora Enso Timber, Johan Oja and Anders Grönlund, my supervisors at the university. For the practical issues the help and assistance of Matti Lehmuskorpi at Honkalahti sawmill, Saku Pänkäläinen at Kotka sawmill and Lars Hansson at the university have been very valuable. The STFI and Skogforsk data from "Skog Massa Papper" added a new dimension to this study and the cooperation of Lars Wilhelmsson, Sven-Olof Lundqvist and Thomas Grahn made it possible. Many thanks for all of your support!

The study have been performed as a part of the Skewood research programme, with equal funding from Stora Enso Timber and Vinnova, the Swedish Agency for Innovation Systems.

Summary

In this study different models for the prediction of dry density from parameters measured on green wood was tried on different datasets.

Data from old literature have been utilized to derive a multivariate PLS model and to compare the significance of different variables. The data was presented as average data for different stands from four different locations in Sweden.

Validation was performed by applying the models on two different datasets; One small sample from southern Finland and the large data gathered by STFI and Skogforsk in the project "Skog Massa Papper". The Finnish data was acquired by measuring properties of log stumps from CT-scanned images.

Derived models were compared with an algebraic derived model and the density correction suggested by EN384. The multivariate model, using green density and position in the stem, can predict dry density of heartwood of Swedish Spruce with a R^2 of about 60 % and a standard error of prediction of 27.4 kg/m³ on a sample disc as its best. This is slightly better compared to single variable models only utilizing the green density as variable. The correlation on the testset was 78 % which is promising when considering that mill specific models should be made in case of industrial implementation which should also improve the models fit on a validation data.

The model should also be tested with respect to the X-ray log scanners ability to measure the variables and the measurement error connected with the measurements.

Index

Introduction **1**
Background and Aim of this Study 1
Strength Grading 1
In General 1
Measuring the Elasticity 2
Vibrational Techniques 3
Scanning Techniques 4
Density as an Indicating Property 4
Other Uses of Density for Sorting 4
X-ray Scanning Technique 5
The X-ray and Tomography Process and Constituents 5
The Generator 5
Interaction with the Body 7
Detecting the Attenuation and Creating an Image 8
A Single Scan 8
Image Reconstruction Algorithm 9
Industrial Varieties of X-ray Scanners 10
The Basic Principle of a X-ray Log Scanner 10
The X-ray Log Scanner in Practice 10
Modelling Dry Density 11
How to Choose Variables 11
Properties of a Log that are Related to Dry Density 12
The use of Green Density 12
The Use of Other Features of the Log 13
Conclusions and Remaining Questions from Literature Study 14
Material and Method **15**
Overview 15
Wooden Material and Data 15
Material for Modelling 15
Material for Validation of Models 15
Finnish Reference Material 16
Processing of SMP Validation Data 16
Data Acquisition of Finnish Reference Material 18
Manual Measurements 18
Scanning Data 18
Laboratorial Measurements 19
Image Analysis 20
Analysis of Data 21
Multivariate Analysis 21
Comparative Calculations 21
Correcting Green Density by EN384 22
Results **24**
Removal of Outliers 24
General Description of the Data 25
Dry Density Prediction Models 26
Validation Using the SMP-Data 29
Validation Using Finnish Log Stumps 34
Discussion **36**
Sources of Inaccuracy 36
Position to Measure on the Log 36
Radial Position and Size of the Measured Area 37
The Effect of Moisture Content 41
Conclusions **42**
Future work **43**
References **44**

Introduction

In order to make the report easier to read the reader is introduced to strength grading in general by a brief summary. This is followed by guidance through available X-ray scanning techniques, both laboratorial and industrial. After that a survey of different models for the prediction of dry wooden density are made as well as a discussion about the density variations of wooden stems. Finally models for the prediction are made and studied in the main body of the report.

Background and Aim of this Study

Strength grading of sawn wood has been a process performed late in the production process of a sawmill. Due to low accuracy of grading equipments and a wide natural distribution of the strength of wood this will inevitably lead to a high yield of products in the lower range of strength classes (Hoffmeyer 1995).

With the implementation of the Eurocode 5 it has been estimated that a 30 % increase of glulam consumption will follow (Johansson et al. 1998). Most glulam lamellas are machine strength graded in order to reach the higher strength classes. This calls for better strength grading machines or processes.

Although the natural bending strength distribution sawn spruce can be described as a normal distribution with average 42.4 MPa and standard deviation of 13.5 MPa (Larsson, et al. 1998), while the highest grade for softwoods according to European standard has a characteristic bending strength of 50 MPa (prEN338:2002 E). This leaves a lot of the natural strength properties of wood unused which is not in favor for wood as a construction material.

By presorting the logs that amount of off-grade can be reduced. Several sawmills in areas where the wood is naturally weaker are pre-sorting by manual means. By utilizing different presorting methods they are able to increase the yield in favorable classes. In the Oceania region for example, presorting of Pinus radiata is done by machine grading. (Anon 2005)

In this report a study of possibly industrially measurable parameters for an automatic pre-sorting of logs has been performed. The objective of this study was to establish a model for the dry density of heartwood with respect to several parameters that could be measured in an industrially process. The final goal should be to be able to set threshold levels for the density value and utilized as a first step in presorting of logs.

Strength Grading

In General

Strength grading machines can not measure the actual strength of any sawn lumber, since that would require that each board first should be broken. Instead a so called Indicating Property (IP), an estimation of the strength, is calculated from different measurable features. (prEN14081-1:2003.)

Since the indicating property always include an error of varying size compared to the true strength some kind of safety factors are included in the settings. The easiest way of determining settings could be by applying the 5 % fractile level, i.e. accepting that for a specific IP level, 5 % of the accepted specimens had a strength lower than the required. With an increasing size of the error, the setting level of the machine is shifted upwards to higher IP, thus higher safety level. At the same time those 5 % ending up in the higher grade are "stolen" from a lower grade, causing the settings for the next lower grade to be increased or even impossible to set (depending on the size of the sample used for derivation of settings).

In the end this means that although roughly more than 50 % of the raw material should fulfil the requirements of strength class C45 (45 MPa bending strength), at present not many producers are producing such high strength classes due to low yield in the desired classes combined with the high yield in reject or unfavourable low grades.

For the calculation of the final IP several different techniques have been used throughout the years.

Measuring the Elasticity

The most commonly used type of strength grading machines have for a long time been different brands of bending machines. By bending each board to a certain deflection and measure the reactive force by which the board pressure the bending roller (Figure 1), the modulus of elasticity (MOE) in flatwise bending is calculated as

$$E_{bending} = \frac{F \cdot L^3}{48 \cdot \left(\frac{t^3 \cdot h}{12} \right) \cdot \Delta},$$

where

t = Thickness of the board,
h = Height of the board,
L = Distance between rollers (supports),
F = Reactive force on the deflection roller,
Δ = Preset or measured deflection on deflection roller,

(Hoffmeyer 1995). Then the well known relation between MOE and modulus of rupture (MOR or bending strength) is utilized to give the final grade to the board. Usually, the correlation between MOE and MOR is in the range of 0.5, depending on species and machine used. Although not a strong result the MOE is by far the best single parameter to measure in order to give an IP to a board.

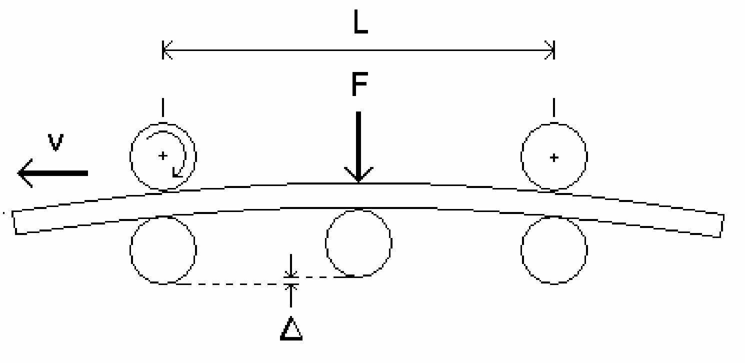

Figure 1. The working principle of a bending type of grading machine.

A natural consequence of the bending machine grading process is that it is made as an isolated element late in the production chain. Usually the grading is made on planed boards of fixed length. To redirect boards of lower grade after the process will not be economically beneficial. Thus, the amount of off-grade can not be adjusted.

Due to deformation (i.e. bow) a board may demand a higher force to be bent in one direction than the other, this calls for a measurement in both flatwise directions or to compensate for the phenomenon by measuring the deformation. Some machine manufacturers have solved this by mounting two machines in series in the same housing. Others have chosen to measure the bow or skewness by different techniques. In older machines the board had to pass two times, one for each face.

Vibrational Techniques

The old fashioned way of measuring the elasticity by bending called for big machinery with relatively high demands on maintenance. Older machines were usually very slow, newer machines might be very large and heavy, thus difficult to incorporate in an existing production line.

The shortcut to get strength grading capability with low investment was the measurement of the dynamic modulus of elasticity. This is based on the Euler-St.Venant theory which states the relationship between the eigenfrequency of a beam, the density, the length and the modulus of elasticity.

A sawn board is brought into vibration by impact of a hammer and the vibration is recorded with some technique. The equation for the eigenfrequency of a vibrating beam in free-free condition and axial vibration is used,

$$E_{A-1} = (f_{A-1} \cdot 2 \cdot L)^2 \cdot \rho ,$$

where

E_{A-1} = Dynamic modulus of elasticity,
f_{A-1} = Eigenfrequency in first axial mode,
L = Length of the board,
ρ = Over all density,

(Ohlsson & Perstorper 1992). The grading with this method is the cheapest but then the density is only estimated, which will reduce the precision and consequently the yield. To get a better prediction with this method would require some measurement of the density.

Scanning Techniques

Since the MOE can not be measured directly without any contact with each board, the grading speed is reduced. The trend amongst constructors of grading equipment is therefore to produce scanning machines who estimate the MOR by other means than by touching each board. Usually the speed can increase but the accuracy of the grading usually gets lower than with the bending type of machine, depending on what kind of parameters that are used in the grading model (Hoffmeyer 1995).

The most tested variables are density and different knot features. These can be found by the use of X-ray and different visual scanners. With respect to the European standard only one brand of grading machines is certified who uses the scanning technique (prEN14081-4:5 March 2004).

Density as an Indicating Property

Predicting strength by the use of density can be done early in the production chain by the use of an X-ray log scanner. The technology is based on the fact that the X-ray attenuation is linearly proportional to the amount of material between the source and the sensor. By using more than one source and sensor the dimension of the object can also be calculated, thereby enabling the calculation of the density. For further improvement back projection calculations must be done, this enables the user to get a more or less detailed picture of internal features of the log, all depending on the number of sources and sensors.

Since green wood contains a lot of water the density will increase accordingly. In order to calculate an IP for a finished product all measurements made on green wood needs to be corrected for the moisture content. After the correction the dry density of the final product can be estimated, thus the indicating property as well.

Between the density and the Modulus Of Rupture (MOR) there is also a correlation, although weak (Larsson 1998). Some reports state that solely by X-ray scanning on logs a correlation similar to that of a bending type of machine can be achieved by using not only density but also different knot parameters (Oja et al 2004).

Many knot features of the log can be found by the use of an X-ray log scanner, although some knots are more difficult to find due to the high density of green sapwood.

Other Uses of Density for Sorting

Strength is only one of several grading prerequisites where density requirement levels exist. Many other standards have requirements of density, like joinery components for flooring and windows (prEN 14220, EN 942). Before the standards finally are adopted, different markets attach different importance to the density measurement and how well it needs to be followed (Anon 2001). The possible benefit of a good predictive model for dry density, and its application in early sawmill process stages, is thus wide and not restricted to strength grading.

X-ray Scanning Technique

This chapter is merely a brief summary of the X-ray scanning technique. The interested reader could find many better or more detailed descriptions on the subject of X-ray scanning and CT scanning (for an example Macowski, 1983) then what I have written or by my sources (Holm 1983, Noll 2003).

The X-ray and Tomography Process and Constituents

An X-ray scanner is a system for imaging the inner part of any body. The system roughly consists of the X-ray generator, the sensor or film and the image reconstructing algorithm in the computerized case.

All x-ray scanners depend on the same fundamentals, whether they are a tomography system or a simple projection system. The main principle is that X-ray photons are generated, projected through a body and the remaining energy is registered by a sensor. In the case of Computerized tomography (CT) this is repeated from many directions and the information from the sensor is sent to a computer in which the image reconstruction algorithm is activated.

There are a large number of varieties amongst CT-scanners, I have limited my description to end up with a Siemens Somatom AR.T, since I have made use of it in the present study.

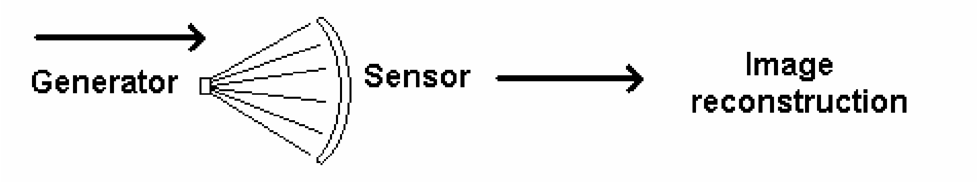

Figure 2. An overview of the X-ray scanning system.

The Generator

The task of the generator is mainly to produce the photons. By heating the cathode by a high voltage, electrons will be leaving the cathode and accelerating towards the anode, the target, a metal plate typically made by Tungsten (Wolfram, atomic number 74). On impact, the accelerated electrons will interact with the target and successively lose their energy. The radiation spectra emitted from the interaction will be continuous due to the "Brems strahlung" with discrete energy peaks as a result from ionization. The continuous contribution is the desired one.

"Brems strahlung" is a name for the process where an electron is passing close to a nucleus and changing its direction due to coulomb attraction between the nuclei and the electron. The direction change will lead to acceleration which in turn forces the electron emitting a photon with a part of its energy. This repeats until the electron has lost all of its energy. The resulting emission intensity spectra will be uniform with the highest frequency of low energy photons ranging up to a frequency of zero close to the maximum photon energy, given from the current over the cathode and anode.

The ionization occurs if the incoming electron hits an electron in one of the electron layers with such a high energy that the atomic bound electron will leave its shell and the atom. The vacancy will be filled by one electron from an outer layer while transmitting radiation equivalent with the difference in bounding energy between the two layers. Thus the wavelength of the radiation will be characteristic for each target material, but the intensity is proportional to the voltage over the anode and cathode. The characteristic radiation spectra will not occur if the acceleration voltage is too low to generate electrons with sufficient energy.

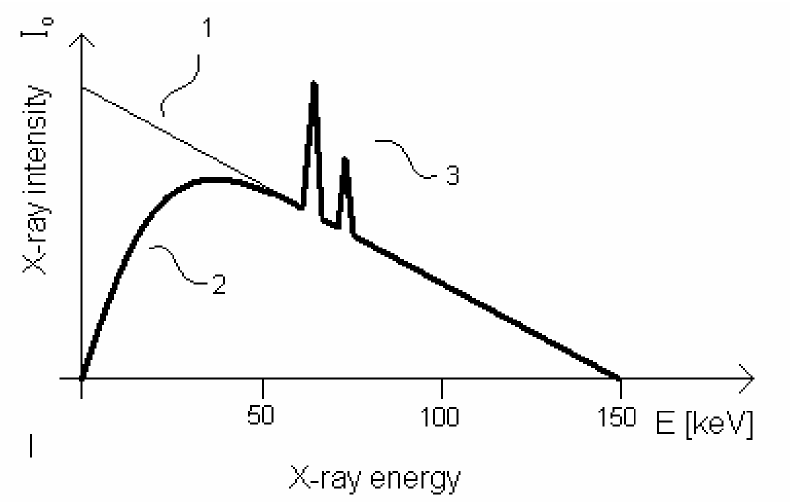

Figure 3. A schematic view of a typical tungsten anode X-ray energy spectra, I_0 (E). 1 marks the unfiltered Brems strahlung spectra, 2 marks the filtered spectra and 3 marks the characteristic peaks of Tungsten K-shell at 60 and 70 keV.

During the process much heat is generated as the efficiency of the process is beneath one percent and a typical operation temperature is around 2500° C. For this reason cooling is necessary. This is one reason for using Tungsten, with a melting point of 3422° C, an other is that the share of the radiation resulting in "Brems strahlung" is proportional to the energy of the electron and the square of the atomic number of the target.

All the constituents of the generator are kept in vacuum. When the X-rays are leaving the vacuum tube they will pass through a glass window and a collimating shielding. The wavelength spectra will thereby be filtered, a so called hardening of the X-ray beam where the glass will absorb photons in the lower range of the spectra. Photons with lower energy are not interesting from image reconstruction point of view, instead this will increase the average energy of the photons in the beam. Further hardening is sometimes done by the use of aluminum or any synthetic polymer as a shield in the path of the beam.

Interaction with the Body

In this text the notation body could mean any body subject to the x-ray radiation. When a beam of photons are passing through a material there will be an attenuation of the intensity since photons are reacting with the matter in the body. Here is just a short summary of the mechanisms that might occur for the energies involved in CT-scanning.

The intensity of the beam when it has passed the body is affected by the size of the body (given by x,y,z for planar X-ray and x,y for CT scanning), the attenuation coefficient of the body (μ). The attenuation coefficient is in its turn depending on the density (ρ) and the atomic number of the body (Z), or its constituents, and the energy of the photons in the beam (E). Thus, the expression for the resulting intensity after passing the body is

$$I_d(x,y) = \int_E I_0(E) \cdot e^{-\int \mu(x,y,E)dz} dE .$$

To complicate the expression more, μ is also depending on the mechanisms of interaction between the photons and the matter it is passing. The four main mechanisms are Rayleigh-Thompson scattering, Photoelectric absorption, Compton scattering and Pair production. The contribution of each of the different energy absorption mechanisms are added to one attenuation coefficient, which will be unique for each body shape and chemical composition.

The Rayleigh-Thompson scattering mechanism is also called coherent scattering. Shortly described it happens when a photon hits an atomic bound electron and the energy is released at the same wavelength but in another direction. This mechanism is not so frequent in the energies used in scanning, the effect might in most cases be neglected.

The photoelectric absorption occurs more often in heavier atoms, or with high Z. The energy from the photon will ionize the atom and give one electron in the K- or L-shell kinetic energy to leave the atom. In the lower part of the energy spectrum this effect is dominating the total attenuation coefficient.

The Compton scattering effect is similar to the photoelectric effect in its mechanism. The difference is that the scattered atomic bound electron will leave one of the outer shells and only consuming part of the energy from the photon. The remaining energy will create a new photon with lower energy. The attenuation coefficient will be proportional to density and remain constant over all energies in the spectrum. Since the photoelectric effect will decrease with increasing photon energy the Compton scattering will be the dominating effect in the higher part of the energy spectra.

Finally this leaves us with an approximation of the final attenuation coefficient for each chemical compound in a body which will serve good within the energy spectra of CT scanning,

$$\mu_{compound}(\rho, Z, E) = \mu_{PE}(\rho, Z, E) + \mu_{CS}(\rho, E).$$

For a certain body the attenuation along a certain travel path is

$$\mu_{total} = \sum_{1}^{N} \mu_{compound\ n} \cdot w_{compound\ n},$$

where *w* represents the volume of the specific compound.

When it comes to wood the differences in chemical composition between species will not affect the attenuation to any greater extent (Lindgren 1991).

Detecting the Attenuation and Creating an Image

To avoid the unwanted effect of detecting photons which have scattered from their original path and not passed as a straight line from the source through the body collimators are used in front of each detector element. When the radiation finally hits the sensor it will interact by some of the mechanisms mentioned above.

By using scintillation crystals visible light is generated in a strength corresponding to the remaining radiation after protruding the body. In series with either a photomultiplier or photo sensitive semiconductor the light pulses are detected and its strength will be set as the in-data to the image reconstruction algorithm for each detector element.

A Single Scan

To be able to build an image which shows the interior of a body as a transversal cut slice the attenuation from many directions needs to be measured. The third generation of CT scanners work by the principle of a rotating source and sensor array, fixed to each other. While the source-sensor is rotating around the body it measures the attenuation twice for each degree.

In order to be able to calculate the attenuation the strength of the initial radiation also needs to be measured, this is done by using a detector array wider than the shadow of the largest body that is allowed for the scanner.

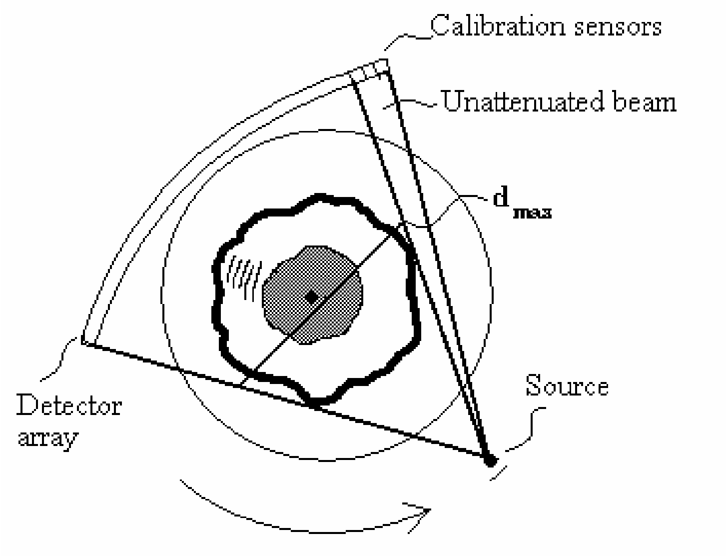

Figure 4. A schematic view of the CT scanner. d_{max} is the widest body that can be scanned in order to keep calibration sensors free from its shadow.

The body remain fixed in its longitudinal position during each scan, depending on the resolution in longitudinal direction the body is translated the desired distance between each scan.

Image Reconstruction Algorithm

Since measurements of the projection are made from so many angles a detailed description of the outer surface is also gained from the scanning. This can be used to calculate and compensate for the travel path for the radiation.

From the 720 scans an image is created by iterative backprojection, Algebraic Reconstruction Technique. Prior to backprojection the fourier transformed attenuation data is filtered by a Shepp Logan filter.

As the beam has got a certain width the resulting image will be representing a slice of the material. Each pixel is thus representing a volume element, a voxel. In the Siemens Somatom AR.T scanner each voxel will be given a value according to

$$CT - number = \frac{1000 \cdot (\mu_{average} - \mu_{water})}{\mu_{water}}.$$

Where the $\mu_{average}$ represents the average absorption coefficient of the material scanned. Each image might be linearly calibrated with respect to density by using known densities in the scanned area, like water and air.

Industrial Varieties of X-ray Scanners

The Basic Principle of a X-ray Log Scanner

To be able to find a position of an inner feature in a body of unknown shape by a transversal scan one direction is not enough. To be able to position the defects at least two scans are needed. With two scanning directions and some assumptions of the density range of the object and its geometrical form, the inner features can be described with an appropriate precision.

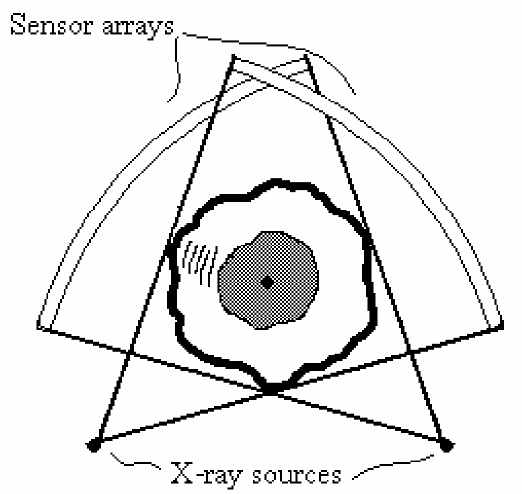

Figure 5. Schematic illustration of the scanner-sensor setup in a two direction logscanner.

The X-ray Log Scanner in Practice

The first generation of "see through" scanners in northern Europe was not utilizing X-rays for attenuation, instead they were equipped with a radioactive isotope which emitted radiation strong enough for detecting inner features of a log. An example is the Swedish gamma-ray scanner "Tina" which used two sources and detectors.

The use of constantly emitting sources was a safety problem for the sawmills. All isotopes have a limited time for decline, which makes the radiation, although predictable, but gradually weaker. Special care was needed when maintenance was called for, like renewal of the source, and special attention had to be paid to the housing of the scanner. (Grundberg 1999).

Several companies began the development of logscanners utilizing of X-ray sources during the 1980's. They made their scanners with different numbers of sources and sensors. In Europe at least three different systems have been commercialized and the number of scanning directions varies between two to four. The difference between the old gamma-ray scanner and the new generation of X-ray scanners has followed the general development in the field of semiconductors. Sensors have become more accurate and data processing much more rapid. Many of the problems with the first generation of logscanners have been over bridged by the general development of better technology.

Many studies have been conducted on the question whether the logscanner completely can replace a 3D outer shape measuring frame. The conclusion is that the 3D frame gives a more accurate description of the shape than the logscanner is able to do. This also depends on the setup of the scanner. (Oja et al. 1998)

The largest problem in the industrial environment is not vibration nor dust but the carriers at the conveyor. If the description of the outer shape of the log is intended to catch the bow of the log, for example, the log must be scanned while locked from rotation and translated in the same plane through the scanner. This calls for a conveyor which is fed through the scanner. At the same time the carriers will then shadow some of the inner features in the log. If the inner features are deemed more important and a gap between two conveyors is introduced, the measurement of the shape of the log is lost.

There have been ideas of combining the best out of the two techniques by adding a one direction X-ray to a 3D measurement frame in order to get an accurate outer shape measurement with a general description of the inner features of the log. For grading of visual grades improvement of the grading result has been showed (Oja et al. 2004). This setup would not call for a gap between conveyors since the X-ray shadow of the steel carriers would be minimal in one direction. The costs of the equipment as well as the maintenance costs are more or less proportional to the number of scanning directions used which would be minimized with this setup.

Modelling Dry Density

Some studies have been made on the variation of moisture content and/or the density of the heartwood in Nordic softwoods. Both longitudinal and radial positions in the tree have been examined as well as different growth conditions and other physical parameters of the tree. The most desired feature to predict has been the basic density, the dry weight through the green volume, since this determines the yield from the log when pulping (Bergstedt & Olesen 2000, Olesen 1977).

When it comes to developing a model which should be practically implemented in a sawmill there are some limitations to that kind of use of data due to the fact that the parameters in the model must be accessible in the process. Data regarding growth conditions are often lost in the logistic handling, leaving the mill with the log as such as carrier of information (Wang 1998). Almost all information must be gathered at the mill for each log.

The goal must thus be to develop a model using parameters that are possible to obtain at the sawmill. The values should be consistent rather than of high accuracy.

How to Choose Variables

The variables to observe are limited by the technique available. Much of the accuracy of a logscanner compared to a CT scanner is lost due to the high speed used, which brings vibration, low resolution and limitations in data processing. The fundamental difference is though the limited number of directions used. While a CT scanner uses some hundreds of directions, the limited number of projections a log scanner uses gives a less detailed description of the inner of the log. Accuracy is also limited due to costs since X-ray sensors and sources are expensive and demands for regular maintenance which reduces the number of directions used, thus also the number of projections.

When it comes to the log, some features are clearly measurable but will not yield any better prediction of the density. The sapwood, for example, has a higher variation in green density compared to the heartwood depending on metrological prerequisites like time of harvest, growth conditions and time between harvesting and measuring.

By choosing variables that might be measured, not only as an exact value, but also as a probability or estimated average, the measurement might get more stable.

Properties of a Log that are Related to Dry Density

The most frequently investigated features of a log that are linked to the dry density are annual ring width, the rate between earlywood and latewood, the share of heartwood and the position in the stem (Bergstedt & Olesen 2000, Wilhelmsson et al. 2002). These variables are all linked to the structure of the wood and gives in some way information of the amount of cell wall matter in a volume of wood.

Since the moisture content of heartwood in the Nordic species usually is a few percent above fiber saturation point (Tamminen 1962 and 1964) most of the water is situated in the cell walls. The structure of the wood will also determine how it absorbs or store water, which affect the green density. So, besides the actual share of cell wall matter in a volume, the green wood density of heartwood is depending on its structure. By assuming that the cell wall matter always absorb equal amount of water at a specific equilibrium climate, a higher density area, i.e. with thicker cell walls, will keep more water than a corresponding area with lower density.

Several other studied properties are linked to properties of the area of origin, as climate and fertility. Since none of these can be revealed in the sawmill process of today, they are omitted in this study. Some properties might be estimated in the process, like the age of the tree or the position of the log in the tree. Then the need for building up models for these variables as well arises.

The use of Green Density

Tamminen (1964) describes how the dry density varies in his test material, both for green and dry spruce. He found that for the inner heartwood in the longitudinal direction the green density is high in the bottom of the trunk, but then rapidly decreasing from 10% of the tree height, with a slower decrease until the height of 30%. After that the density is quite stable. For the sapwood the green density is increasing until the middle of the tree and then slowly decreases.

He showed that the same pattern is evident in dry inner heartwood while the pattern of dry sapwood is not as consistent. His conclusion was that regional growth parameters had a greater impact to the density of this part of the stem.

For older trees the density is much higher in the core of the heartwood than in the surrounding heartwood, but this is not found in younger trees. He relates this to degradation of the older trees which causes more water to be stored in the core, i.e. a higher moisture content (“vattved” in Swedish). He had also some problems with defining the outer heartwood from the inner sapwood which caused some inaccuracies in the values for outer heartwood. This is generally the problem for spruce since the border is not always clearly defined except in most cases of freshly sawn lumber.

Sometimes a wood type is found which often is referred to as "intermediate wood" or incompletely developed heartwood. This wood type has a moisture content in between sapwood and heartwood which is irregularly distributed in the transversal cut. (Sandberg 2004). To define the border between heartwood and sapwood for a scanner might be an impossible task in such cases.

Wang (1998) studied some properties linked to the dry density of Scots pine. She found that the best feature to measure of a log, in order to predict dry density, is the green density of the heartwood. She found that by measuring the density of a number of annual rings from the pith, the total density of the log could be predicted with a correlation up to 0.93. The higher up in the stem and the more annual rings included the better correlation. The pattern is recognized, and also given for Scots pine by Tamminen (1962), that the slow decrease of the density in the upper half of the stem is more linear than in the first 30 %, which makes it easier to predict.

Finally, Wang found that the correlation between green heartwood and the dry density of the whole log were in the range between 0.69 and 0.75, depending on which part of the stem that was studied. She also stated that the uncertainty of the prediction was higher when using green sapwood in the model.

Grundberg (1990) concludes that the density variation due to dehydration of the log is least in the heartwood. Even after 40 days in an outdoor environment the MC of the heartwood had not decreased significantly while the sapwood had a weight reduction of about 35 %.

The Use of Other Features of the Log

Although used for determining the basic density, some Silvicultural studies make use of growth conditioned parameters. Wilhelmsson et al (2002) made a thorough study of parameters to use and modeled using stand data such as annual temperature sum and sample disc data such as average annual ring width and diameter under bark. By using those parameters they achieved a degree of determination of 0.50. When using proportion of latewood and annual ring width they achieved a degree of determination of 0.39 for spruce, which improved to 0.55 when adding temperature sum. The increase shows the difference between identical wood at different stands. Up to date there are no studies made on how well an industrial scanner can measure neither the latewood content nor the annual ring width.

Wilhelmsson et al based their model partly on a model made by Olesen (1976) where he used an expression based on the average annual ring width as the only feature of the log, and added parameters depending on growth conditions. Bergstedt and Olesen (2000) tried to further improve this formula by adding field measurable features such as position in the stem. They found difficulties with the prediction of density on sample disc level, with R^2 between 0.26 and 0.47 for the model depending on model and the material it was based on. The sole use of annual rings for the prediction caused inaccuracy as the number of annual rings got fewer.

They concluded that the dry matter content of a stem could be estimated by using only annual ring width, disregarding growth conditions and tree height. Only in very young trees this seemed to be a problem due to the high content of juvenile wood.

Olesen (1977) claimed that the variation of basic density in the juvenile wood is decreasing from the pith until the 8th to 10th annual ring, thereafter increasing to a mature wood level at ring 15 to 20.

Conclusions and Remaining Questions from Literature Study

Taking into consideration the properties mentioned above some good variables to include would be the position in the stem, in order to adjust for the higher density in the butt log. The heartwood content and annual rings would also be included, although their importance would surely be different at different growth locations. The green density would however be the most important variable.

The best measurement position in the cross section appears to be in the center of the log, in order to reduce the bias from an unclear border between heartwood and sapwood. The risk would be to overestimate density of older logs with beginning degradation.

If the moisture content in the whole heartwood is approximately equal, the prediction of density from the juvenile wood would be somewhat lower than if the prediction was based on the mature wood. The risk with this measurement position is that the variation between the mature and the juvenile wood is big. To have an easily defined measurement position and a low risk of interference from sapwood or intermediate wood might compensate for this.

Material and Method

Overview

In order to facilitate the reading of the method the figure gives a brief description of the path of the method (Figure 6).

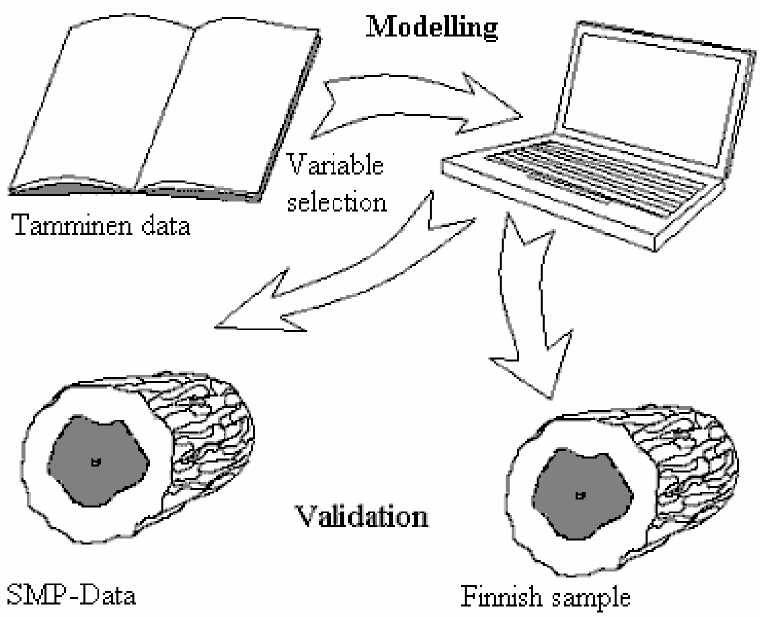

Figure 6. Schematic overview of the modeling and evaluation method.

Wooden Material and Data

Material for Modelling

For the modelling data from an old Swedish study was used, from now on referred to as the Tamminen data (Tamminen 1964). Tamminen has examined 77 Spruce stems from four different parts of Sweden. Each geographic origin is represented by four stands, and each stand is represented by 2 to 7 trees. Each tree is represented by up to five discs, from 0, 10, 30, 50 and 70 % of the height of the tree. All data is given as average for each stand.

Material for Validation of Models

For validation of the model, data from a project named "Skog Massa Papper" (SMP) managed by STFI and Skogforsk was used (Wilhelmsson et al. 2002).

This material comprised 252 spruce stems from 42 different stands with various growth conditions. Information on growth condition was combined with data on physical properties from each tree, sample disc and annual ring. Most of the SMP data used in this study was acquired by the use of a CT-scanner.

For a thorough description of the material see the reference material.

Finnish Reference Material

Validation was also performed on 20 log samples from southern Finland. The logs had a top diameter of between 201 and 218 mm on top of the bark, measured 150 mm from the top of the log. Top, middle and butt logs were represented.

Processing of SMP Validation Data

The parameters used in this study was not readily obtainable from the SMP database, thus some parameters had to be created or replaced by similar to the ones used in the modelling.

No heartwood density was given at all in the material so the dry density of heartwood was replaced with the dry density of the sample disc. In that way both the heartwood and the sapwood was represented in the observed dry density value.

The green density of heartwood could be calculated by using the share of heartwood, diameter under bark, the annual ring width for each annual ring and its density.

The amount of heartwood was given as the share of heartwood area in each sample disc. That information was combined with the diameter under bark of each disc to give the heartwood radius by

$$r_{HW} = \sqrt{\frac{HW}{100} \cdot \left(\frac{D_{ub}}{2}\right)^2} ,$$

where

r_{HW} = Approximate radius of the heartwood [mm],
HW = The share of heartwood area [%],
D_{ub} = Sample disc diameter under bark.

With the approximate heartwood radius known, an algorithm was made to find the cumulative annual ring widths closest comparable to $r_{HW.}$ The green heartwood could then be calculated by

$$\rho_{u,u\,HW} = \frac{\sum_{1}^{N} \rho_{AR\,i} \cdot \pi \cdot \left(r_i^2 - r_{i-1}^2\right)}{\pi \cdot \sum_{1}^{N} r_i^2}$$

where

$\rho_{u,u\,HW}$ = Green heartwood density [kg/m³],
r_i = Annual ring width of the i^{th} annual ring [mm],
N = Number of annual rings constituting the heartwood.

Since the green density measurement of the annual rings had been made in two directions, northern and southern, the average of these two were used to be able to get as close as possible to the original measurement.

When applying the models on the SMP data each sample disc was treated as one individual observation regardless of the fact that there were several discs from each tree.

The sample disc position in the stem was given accurately, as well as the height of the tree which caused this data to be the most accurate for applying the models with respect to the variable position in the stem.

Data Acquisition of Finnish Reference Material

For validation of the model Finnish material was selected at a sawmill in the south of Finland during mid winter. Several measurements were made at the sawmill both manually and with different scanning techniques. Sample pieces, in average 400 mm long, were cut in the butt end of each log by chainsaw and thereafter wrapped into plastic and sealed. In that state they were transported to a laboratory. All storage before analysis was made below the freezing point.

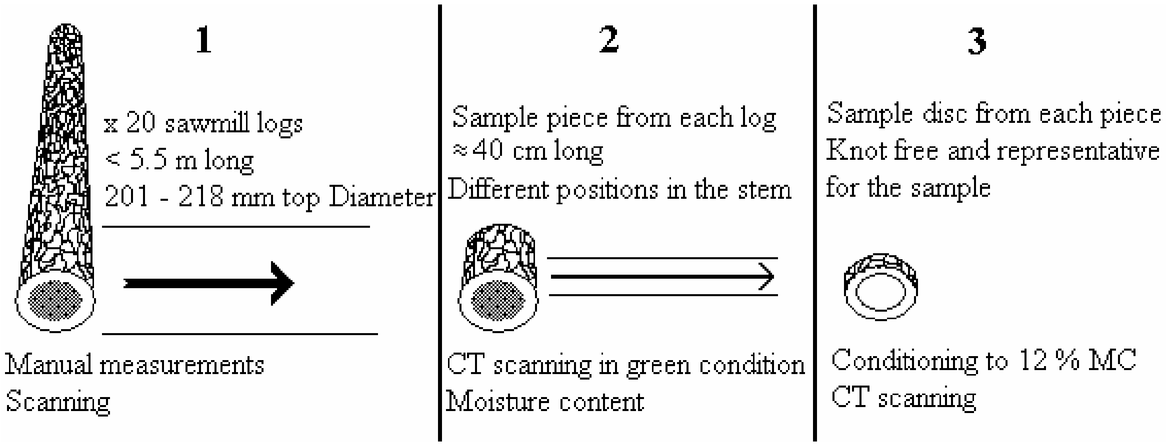

Figure 7. The general data acquisition procedure for the Finnish reference material.

Not all of the methods described below have given results which have been utilized in this study. The description in those cases is given mainly to describe the experimental work which has been performed within the limit of this study.

Manual Measurements

Length, top diameter and average annual ring width for the 20 first rings from the pith were measured. The log type (butt, middle or top log) were estimated.

Scanning Data

The outer shape of the logs was measured by a 3D laser scanning frame. The inner features were measured with an X-ray log scanner with four directions. The scanner utilized two separate conveyors with a gap in between for the X-ray beam. The spiral grain angle was measured by the scattering of laser light in the wood surface.

Figure 8. Scanning in X-ray (left picture) behind lead curtains. The laser spot on the surface of the log is due to the grain angle measurement, mounted above the log. 3D measurement (right picture).

For the boards made from the remains of each log both machine vision scanning in RGB spectra and X-ray scanning in one direction were made in an industrial environment. All industrial scanning was made in normal production speed.

Laboratorial Measurements

The sample log pieces were scanned in a Siemens Somatom AR.T medical CT scanner. The slice width was 5 mm and the spacing between scans 5 mm. The scanning took place shortly after the industrial scanning.

After scanning a representative disc was cut from each log piece. The sample disc was free from knots. It was conditioned down to 12 % MC and scanned again in that state.

The green moisture content for sapwood and heartwood was measured for each log by the oven dry method. For that purpose a knot free piece, approximately 40x40x40 mm, was cut in each wood type.

Annual ring width of each log stump was measured as the radius for the twenty innermost annual rings.

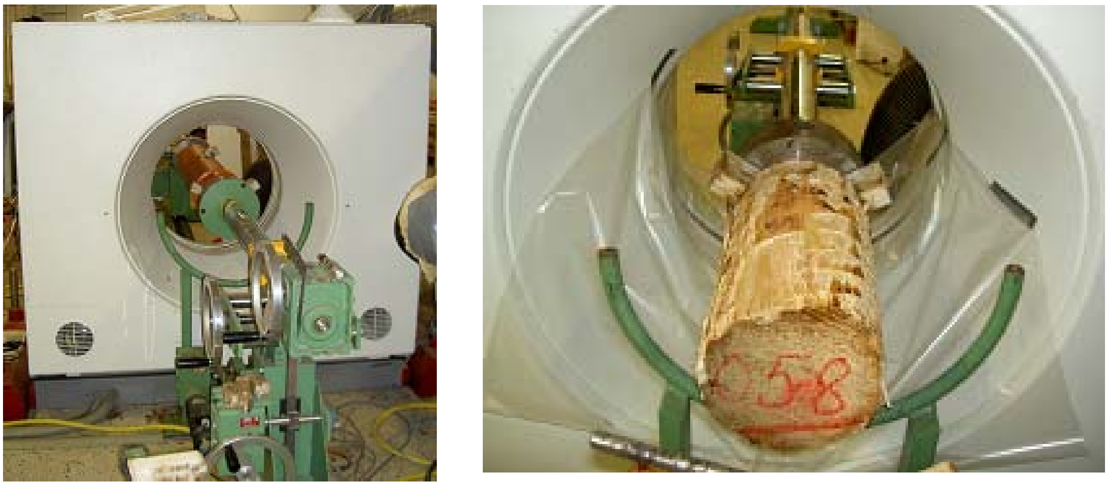

Figure 9. The CT scanner and its feeding mechanics. A dummy mounted in the left picture. Plastic as water protection in the right picture.

Image Analysis

For each sample the density in green state and 12 % MC was measured. This was made in the software Scion Image for Windows, version Beta 4.0.2 (Anon 2000). By measuring the green density at a longitudinal position corresponding to the position of the representative disc comparable values were gathered. The density value was set as the average density for a box area covering the 30 innermost annual rings. The values of the image were calibrated against the density values of water and air at 20 °C since a water phantom was incorporated in each scan.

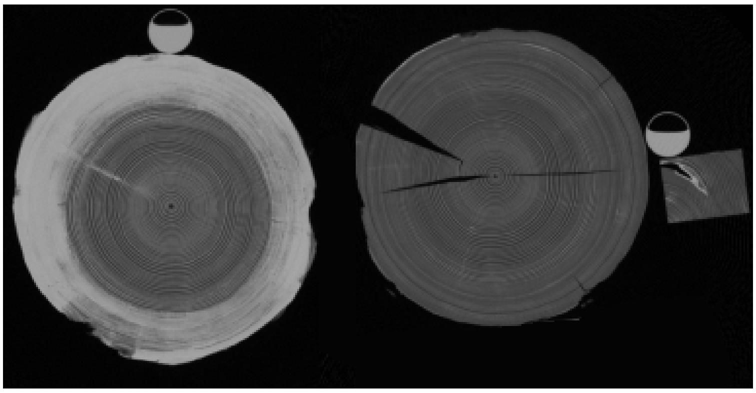

Figure 10. The same log sample in green (left) and in conditioned state (right). The slice is not the same but shown to give an example of the use of a water phantom. The conditioned image was used to acquire dry density data for verification purposes.

Analysis of Data

Multivariate Analysis

Some of the data given by Tamminen in appendices in part two of his report serie was transferred to a spreadsheet. The multivariate analysis tool Simca-P+ v 10.0.2 (Anon 2004) was used to model the data.

By using PLS, Partial Least Squares projection to latent structures, data with more variables than observation as well as dependent variables, with noise present or even missing measurement, can be used as input to a model. This is usually the case when modelling wood properties, thus making PLS an appropriate selection of modelling tool (Lindgren 1994).

Three models were considered; Initially a general description of the material was made by performing a PCA analysis on all the data (Eriksson et al 1999). Secondly one model covering all the possibly measurable variables was made in order to predict dry density. Then a model where variables stated as important in the literature study was used. Finally a model was made from the strongest variables which are possible to measure or estimate in a sawmill with the use of an X-ray log scanner.

Table 1. Description of the variables in the models.

Variable	Description
Long_Pos_stem	Longitudinal position in the stem. 1, 10, 30, 50 and 70 % from the butt.
Location	Growth location An index number ranging from 1-4.
Population	Each location consisted of four sub locations, here denoted by population. An index number ranging from 1-16.
Time_harvest	The relative time of harvest. Expressed as share of the year. (I.e. June=0.5.)
Moisture_content	Moisture content in the heartwood. [%]
Green_density	The green density, measured by manual means. [kg/m^3]
Dry_density	The oven dry density, measured by manual means. [kg/m^3]
Age_max	The age of the oldest sample stem from each population. [Years]
Age_min	The age of the youngest sample stem from each population. [Years]
Age_avg	Average age of the samples from each population. [Years]
Bonitet	Fertility index of the growth site. In this case varying from II-V.
Altitude	Altitude of the growth site. [m above sea level]
Latitude	The latitude of the growth site. [°]
AvgARW	Average annual ring width in the heartwood at a given position. [mm]
Rel_HWD	Share of the stem diameter consisting of heartwood. [%]

Comparative Calculations

In order to compare the results from modelling a simple correction between green and dry density was made. This one is utilizing a linear approximation between the volumetric shrinkage and the green density from the Tamminen data and a linear relationship between shrinkage and moisture content, valid when $u \leq u_{fs}$,

$$\beta_v = \left(2 + 2 \cdot \frac{\rho_{0,0}}{100}\right) \cdot \frac{u}{u_{fs}} \quad [\%]. \tag{1}$$

Tamminen defined the relation between shrinkage and volumetric change as

$$\beta_v = \frac{V_u - V_0}{V_u}. \tag{3}$$

The equation for density at different moisture contents with equation (2) and (3) substituted becomes,

$$\rho_{0,0} = \frac{m_0}{V_0} = \frac{m_u}{V_u} \cdot \frac{1}{(1+u)\cdot(1-\beta_v)} = \rho_{u,u} \cdot \frac{1}{(1+u)\cdot\left(1 - \frac{1}{100}\cdot\left(2 + 2\cdot\frac{\rho_{0,0}}{100}\right)\cdot\frac{u}{u_{fs}}\right)}. \tag{4}$$

By solving (4) for $\rho_{0,0}$ we get

$$\rho_{0,0} = 50 - \frac{2500 \cdot u_{fs}}{u} \pm \sqrt{\frac{25 \cdot 10^6 \cdot u_{fs}^{\;2}}{4 \cdot u^2} - \frac{10^6 \cdot u_{fs}}{4 \cdot u} + \frac{10^3}{4} + \frac{5000 \cdot u_{fs} \cdot \rho_{u,u}}{u + u^2}}, \tag{5}$$

and by using the positive root the correction to dry density can be made. When the moisture content is higher than the assumed fibre saturation point equation is reduced since all shrinkage may be considered. Solving Equation 4 yields then,

$$\rho_{0,0} = 2450 \pm 50 \cdot \sqrt{\frac{(2401 + 2401 \cdot u - 2 \cdot \rho_{u,u})}{(1+u)}}, \tag{6}$$

and by using the negative root the density is given.

The fibre saturation point for the inner part of the heartwood is close to constant throughout the Tamminen material, $u_{fs} \approx 30$ %. For the comparative calculations an average moisture content of 40 % in the heartwood has been assumed. This is well in accordance with the actual figures for the Tamminen material.

When applying the model to the SMP data an average moisture content of 30 % was wrongly assumed in order to compare with the EN384 model.

Correcting Green Density by EN384

In the European standard “Structural timber – Determination of characteristic values of mechanical properties” a method for correcting the density to a reference condition is suggested (EN384). The method is normally used to correct deviations in the moisture content range from10 % to 18 % to the equilibrium moisture content at the climate 20 °C, 65 % RH. It should compensate the density with respect to both shrinkage and moisture.

The standard suggests a decrease of 0.5 % of density for every percent moisture content above the reference of 12 %. This can also be written as

$$\rho_{corr} = \left(1 + \left(0.005 \cdot \left(12 - u\right)\right)\right) \cdot \rho_u ,$$

where

ρ_{corr} = The density corrected to reference condition,
ρ_u = The density at moisture content u,
u = Moisture content [%].

The equation should be regarded as valid below fibre saturation point which calls for an additional part which should correct for the additional weight at moisture content above the fibre saturation point.

When this model was applied to the validation material a moisture content of 30 % was wrongly assumed in order to reduce the effect of considering a shrinkage above the maximum one, from fibre saturation point down to dry.

Results

Removal of Outliers

Modelling was initially made by using all the data. Three observations were removed after the initial PCA study. The reason was that the moisture content was many times above fibre saturation and close to the moisture content of sapwood. Notations regarding the difficulties of measurements related to the borderline between heartwood and sapwood in that specific growth area was also made in the original report. All deviant observations came from the 70 % longitudinal position of growth area 1 (Figure 11).

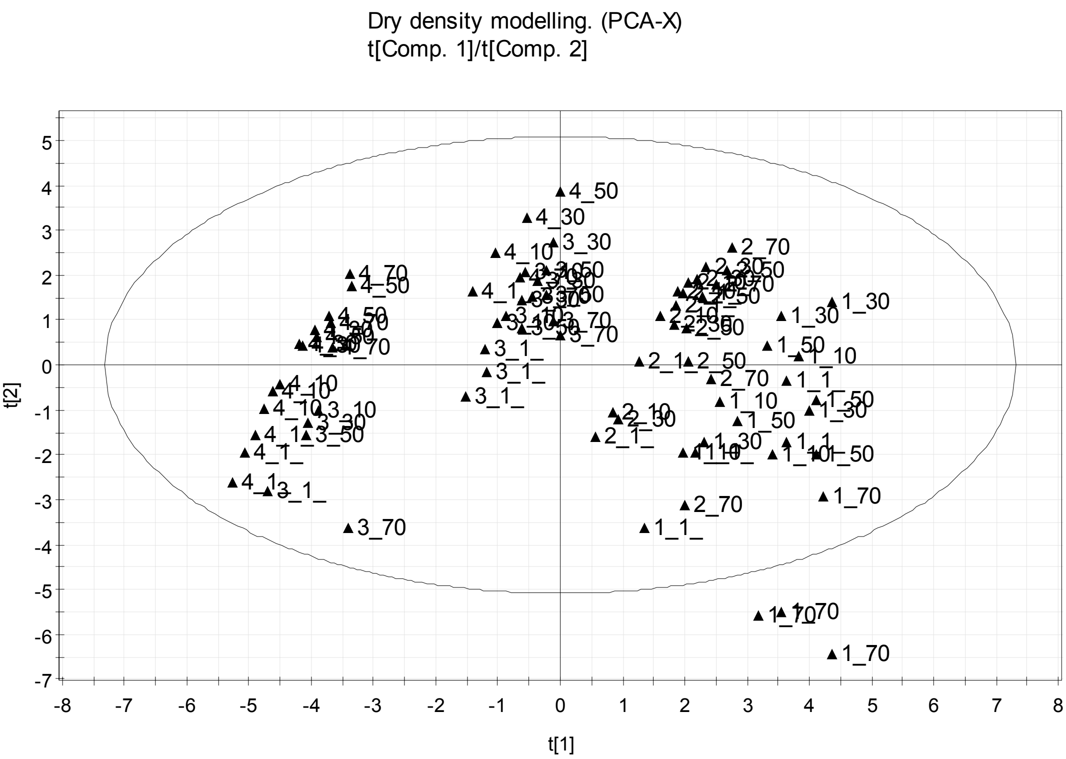

Figure 11. The Score scatter plot of the first PCA. Notation is made according to "Location_Position in the stem". Notice the outliers with deviant moisture content. For an algorithm in an industrial application those observations would not be detected as heartwood thus left aside from prediction.

The score and scatter plots (Figure 11, Figure 12) should be viewed at the same time since the score scatter plot is explaining which observations that are related to which variables. In this case (Figure 11) the variables marked "1_70" outside the oval shape are heavily influencing the model by a low value on origin, a high value of moisture content, density, time of harvest (late) and annual ring width.

General Description of the Data

The first evaluation after removing outliers was made in order to test the over all explanatory abilities of the material and to study if the relations described in the reference literature were confirmed. By using PCA a total R^2X of 0.988 and Q^2 of 0.870 was achieved (Figure 11 with minor adjustments and Figure 12).

The Q^2 value gives an indication of the stability of the model, the cross validated model fit or "the goodness of prediction" (Wold 1978). Shortly the method can be described as modelling repeatedly with several values from different observations removed from the dataset, followed by a calculation of a partial predicted sum of squares (partial *PRESS*) from those observations removed. This is repeated until all values from all observations have been left out from modelling once. Finally, all partial *PRESS* is summed and

$$Q^2 = 1 - \frac{PRESS_{tot}}{SS_{tot}}.$$

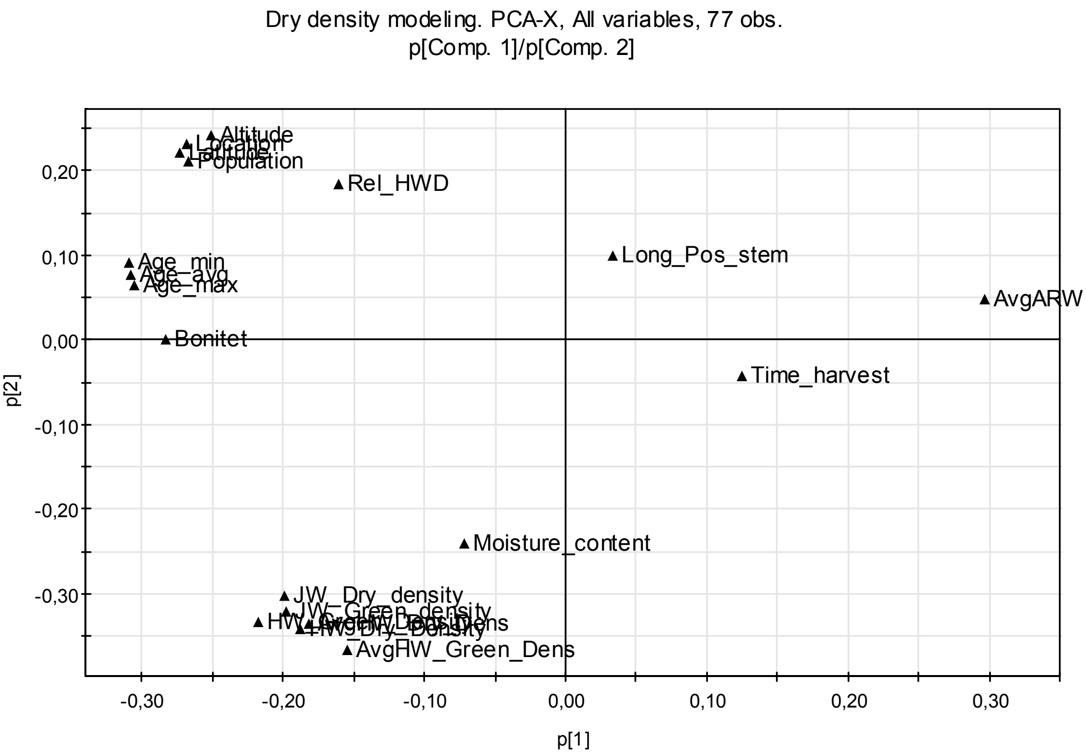

Figure 12. Scoreplot of the PCA analysis. JW is the notation for the inner heartwood observations.

The score plot of the PCA analysis of the Tamminen data (Figure 12) illustrates how variables are related. This is found by thinking a straight line through origo and projecting the variables in a right angle to this line. The further away from origo the projected position is situated the stronger the correlation. If they end up close to origo they are barely relevant but if they end up on the same side of origo as the examined variable they are positively correlated and vice versa. Taking the JW_Dry_density as an example the

Green_density and Moisture_content is positively correlated, while Long_pos_stem, AvgARW and Rel_HWD are negatively correlated.

The growth location is defined with the lower values in the south of Sweden, causing the location to be negatively correlated with density. The age variables are barely positive correlated with the density.

Most important, the measurable features of the log are those with the strongest correlation to the density. The annual ring width, heartwood diameter and the green density are all correlated to dry density.

Some causal relations do exist. All material at each growth area was estimated to be cut at the same time, which is obvious from the plot. The clustering of the observations from different origin in this case is partly explained by the variable origin which naturally divides the logs into clusters. When these variables are removed the clusters becomes less obvious, the overall explanatory ability of the model is still as good as without them, meaning that the log features covariate enough to explain the properties of the log without the growth variables.

Dry Density Prediction Models

Several models were built in order to evaluate the significance and contribution of the available variables. The derived variables average age (Age_avg) and time of harvest did not fulfil the significance criteria (95 % significance level based on Jack Knifing (Bradley 1983)) and were removed accordingly. The same applied to the average relative heartwood diameter (Rel_HWD). A model (Model 1, Table 2) with those variables present is presented anyway for verification purposes (Figure 13).

Table 2. Description of the variables that constitutes each model, training set. Model 1 contained non significant variables on the 95 % level.

	Model 1	**Model 2**	**Model 3**	**Model 45**
Analysis model	PLS	PLS	Linear regression	PLS
R^2	0.822	0.791	0.741	0.788
Q^2	0.788	0.784	0.736	0.779
PC	2	1	-	
RMSE, Observed vs predicted	18.4	19.8	22.1	19.94
Observations	77	77	77	77
Model				
Constant	319.03	240.42	179.84	357.528
Long_Pos_stem	-0.428	-0.634	-	-0.407
Time_harvest	-12.93		-	-
Green_density	0.330	0.417	0.487	0.267
Age_avg	0.067		-	-
AvgARW	-20.05		-	-27.21
Rel_HWD	-0.419		-	-

Model 1 made it clear that some measurable variables did not contribute significantly to the prediction result (Figure 13).

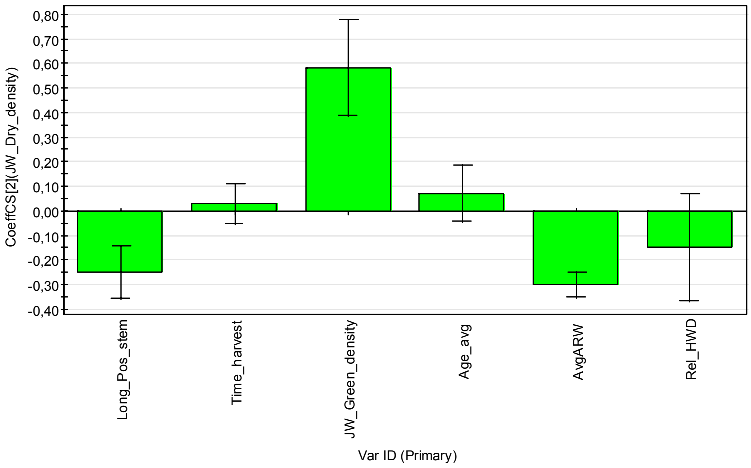

Figure 13. Jack knife of the PLS model constituting all variables (Model 1). The coefficient values are presented as scaled and centred with 95 % confidence interval.

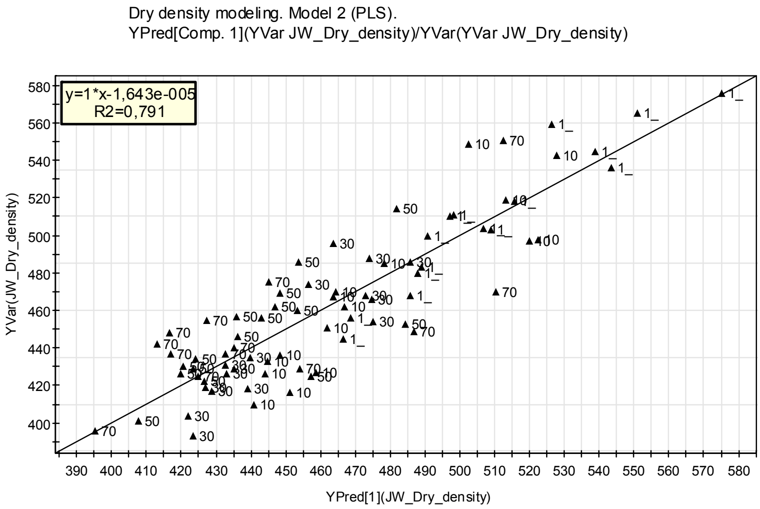

Figure 14.

The observed versus predicted plot for Model 2.

Notice how evenly the observations from different position in the stem are distributed.

RMSEE = 19,8243

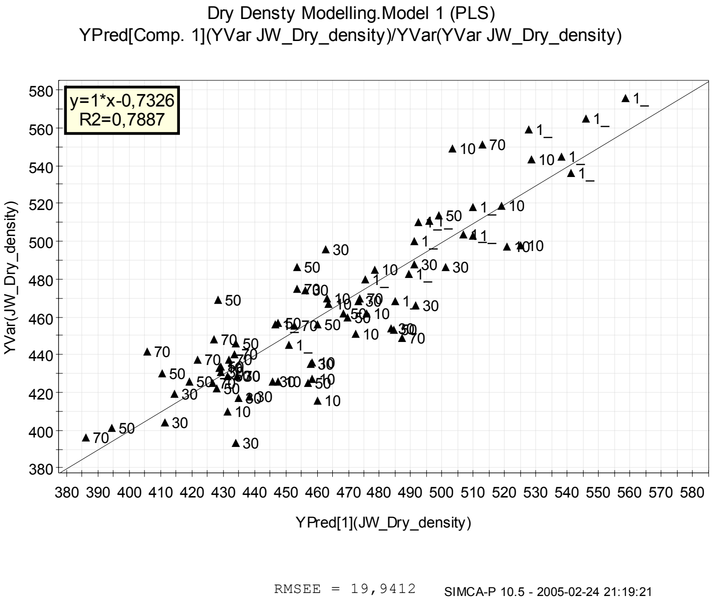

Figure 15.

The observed versus predicted plot for Model 1.

This model is over fitted since non significant variables are still included.

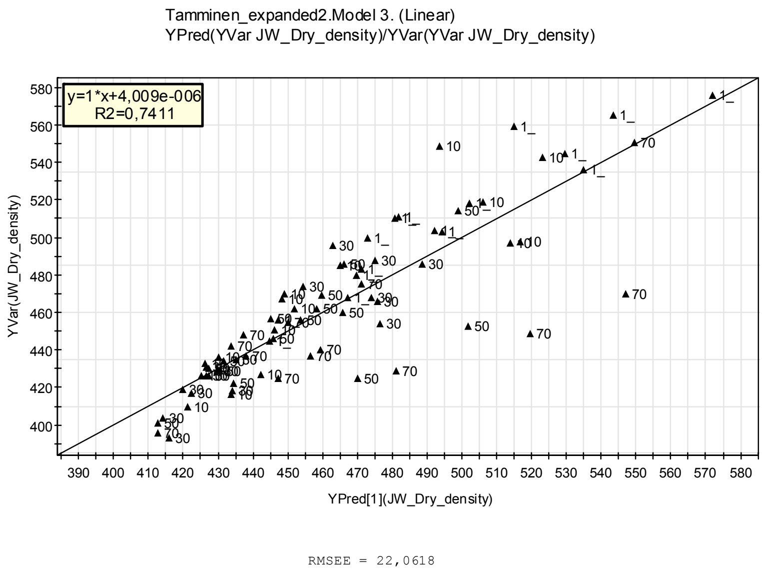

Figure 16.

The observed versus predicted plot for Model 3.

Notice that the observations in the upper part of the stem tend to be overestimated when there is no correction for the position in the stem, and the higher moisture content there.

The normal probability plot for Model 3 showed a non-linearity while Model 2 was normally distributed. This could also be expected since there is a linear relationship between the position in the stem and the density in the sample material.

Validation Using the SMP-Data

Some data was unused since the algorithm combining the heartwood radius with the corresponding number of annual rings could not always find a match. The number of accepted samples is given with each model (Table 3, Table 4 and Table 5).

The analysis was divided into two main cases and sub cases within these:

1. Division in potential saw logs with a diameter under bark ≥ 120 mm and potential pulp logs with a smaller diameter (Table 3, Table 4):
    a. Sub groups depending on the area share of heartwood the prediction was based on:
    25 %, 50 %, 75 % and 90 % heartwood area, counted from pith and outwards.
    b. All models applied.
2. Only saw logs considered (Table 5):
    a. Division into the least number of annual rings the prediction was based on: ≥40, ≥30, ≥20 and ≥10 annual rings.
    b. All models applied.

Table 3. The R^2 and standard error on the prediction for the sample discs with a diameter under bark ≥ 120 mm. Divided into classes depending on how big share of the heartwood the calculation was based on.

R^2 [%]				
HW Share / Model	25 %	50 %	75 %	90 %
N Samples	229	265	323	336
Average N AR	8.4	17.3	25.1	31.5
M2	18.6	23.6	29.0	27.8
M3	16.1	24.1	30.2	27.1
M45	9.8	11.5	15.9	17.5
Equation 6	15.5	23.7	29.8	26.9
EN 384	16.1	24.1	30.2	27.1
SE_y [kg/m³]				
M2	38.6	37.0	35.4	34.7
M3	39.2	36.8	35.1	34.9
M45	40.6	39.8	38.6	37.1
Equation 6	39.3	36.9	35.2	34.9
EN 384	39.2	36.8	35.1	34.9
Average Absolute Error [kg/m³]				
M2	43.7	43.7	42.4	33.2
M3	42.1	31.0	27.8	29.7
M45	47.8	45.8	42.5	36.7
Equation 6	35.8	42.1	37.7	57.7
EN 384	55.5	46.0	45.1	72.3

Table 4. The R^2 and standard error on the prediction for the sample discs with a diameter under bark < 120 mm. Divided into classes depending on how big share of the heartwood the calculation was based on.

R^2 [%]				
HW Share / Model	25 %	50 %	75 %	90 %
N Samples	299	331	341	347
Average N AR	2.5	5.0	7.7	9.5
M2	22.1	20.7	23.8	21.8
M3	16.7	15.0	15.5	14.5
M45	16.6	18.6	29.8	23.8
Equation 6	16.6	14.9	15.0	14.0
EN 384	16.7	15.0	15.5	14.5
SE_y [kg/m³]				
M2	39.6	40.8	39.0	39.0
M3	40.9	41.9	41.1	40.8
M45	41.0	41.0	37.5	38.6
Equation 6	41.0	41.9	41.2	41.0
EN 384	40.9	41.9	41.1	40.8
[kg/m³]				
M2	48.2	49.3	43.3	37.1
M3	37.0	36.5	38.1	43.7
M45	43.4	41.3	35.4	33.9
Equation 6	66.4	65.9	76.9	99.8
EN 384	75.9	76.6	89.7	113.3

Table 5. The R^2 and standard error of the prediction for the sample discs with a diameter under bark ≥ 120 mm. The calculation was based on 75 % share of heartwood and the minimum number of annual rings (AR), counted from pith and outwards, is given for each model.

R^2 [%]				
HW Share / Model	10 AR	20 AR	30 AR	40 AR
N Samples	286	162	79	43
Average N AR	27.5	37.3	51.6	66.6
M2	35.3	46.4	55.5	60.8
M3	34.7	41.4	49.7	55.8
M45	15.1	17.4	35.5	49.3
Equation 6	34.3	40.6	49.0	55.0
EN 384	34.7	41.4	49.7	55.8
SE_y [kg/m³]				
M2	34.2	31.4	27.6	27.4
M3	34.4	32.8	29.3	29.0
M45	39.2	39.0	33.2	31.1
Equation 6	34.5	33.1	29.5	29.3
EN 384	34.4	32.8	29.3	29.0
Average Absolute Error [kg/m³]				
M2	42.5	36.4	28.1	23.7
M3	27.6	25.9	21.9	23.2
M45	41.3	35.6	30.8	35.8
Equation 6	36.3	34.1	38.9	46.3
EN 384	42.2	40.4	50.3	59.8

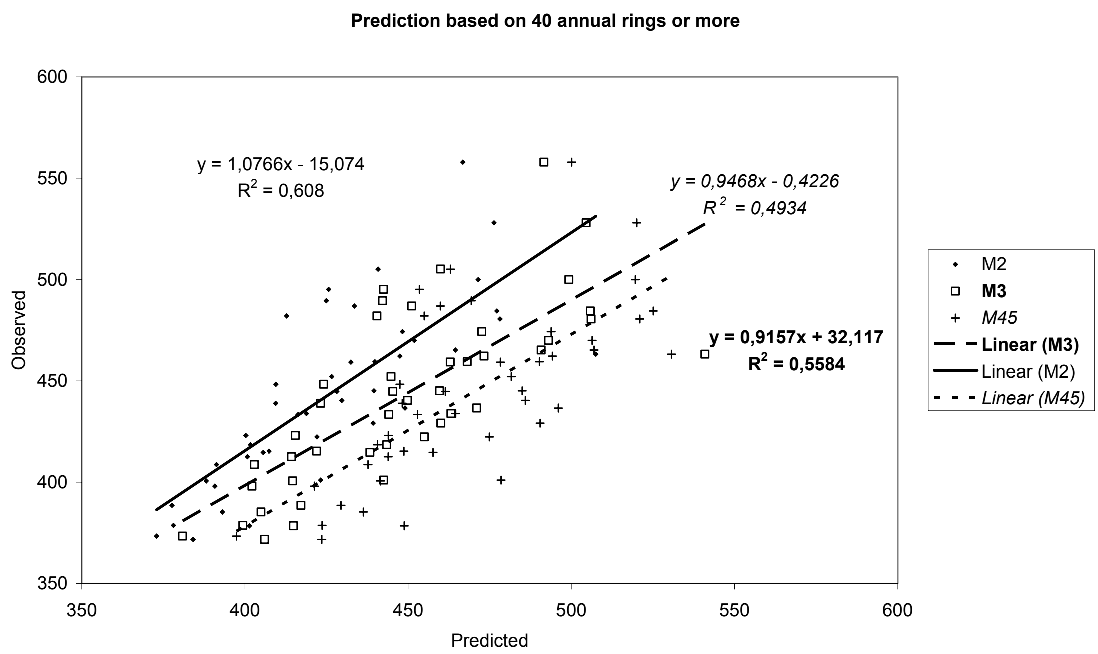

Figure 17. The prediction based on 75 % of the heartwood area and at least on 40 annual rings. Model 2, Model 3 and Model 45 applied to SMP verification data.

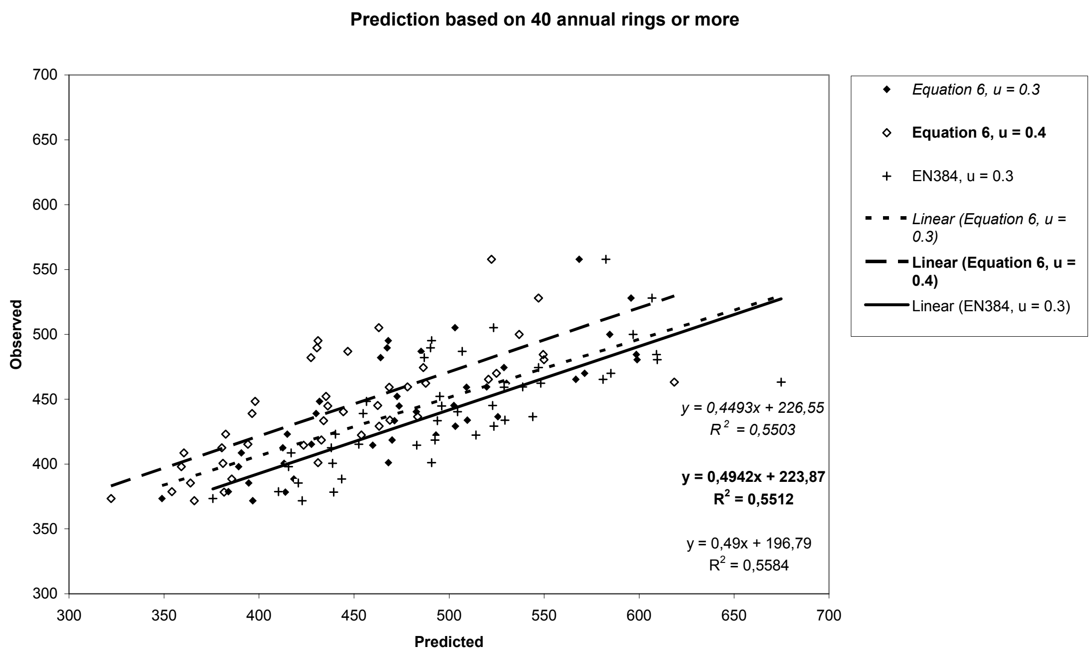

Figure 18. The prediction based on 75 % of the heartwood area and at least on 40 annual rings. Equation 6 with two different assumed moisture contents and the model suggested by EN384 applied to SMP verification data.

Validation Using Finnish Log Stumps

The average moisture content of the sample discs were 40 % in the heartwood, with a standard deviation of 6 %. In the sapwood the corresponding figure was 164 % and 19 % standard deviation.

The Equation 6 and EN384 models were both applied by using an estimated moisture content of 30 %. In all cases no correction was made to the measured dry density which was acquired at the reference climate corresponding to 12 % equilibrium moisture content.

The measurement position in the stem was estimated by using an estimation of the log type (but log, middle log and top log) and an assumption of maximum four logs of the same height in the tree.

Table 6. The R^2 and standard error on the prediction for the Finnish sample discs. The prediction was based on an area corresponding to "the inner heartwood" given by Tamminen compared to the whole heartwood. The twenty innermost annual rings based the annual ring width.

R^2 [%]		
HW Share / Model	Inner heartwood	Heartwood
N	20	20
M2	48.6	41.1
M3	58.6	61.0
M45	49.6	27.8
Equation 6	57.8	60.7
EN 384	58.5	61.0
SE_y [kg/m³]		
M2	24.4	19.9
M3	21.9	16.2
M45	24.1	22.0
Equation 6	22.1	16.2
EN 384	21.9	16.2
Average Absolute Error [kg/m³]		
M2	19.7	17.0
M3	19.3	15.1
M45	21.6	25.2
Equation 6	40.0	30.8
EN 384	38.6	33.6

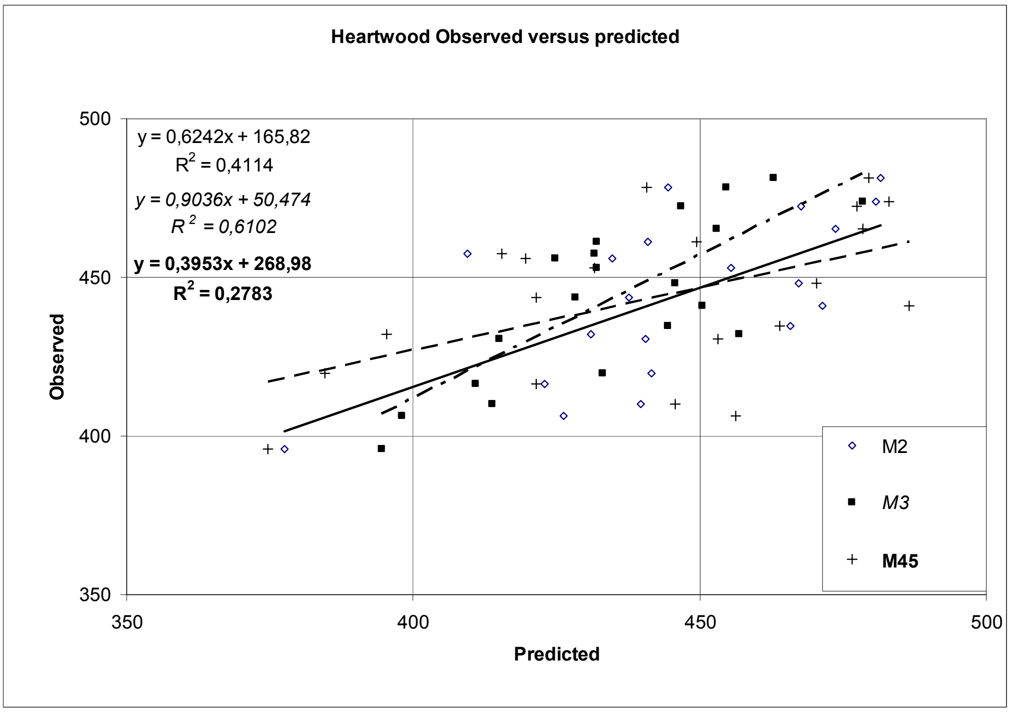

Figure 19. Derived models applied to an area measured as the average of a box containing the whole heartwood. Same area is measured in both green and dry state. Annual ring width included in Model 45 measured only as the first 20 annual rings.

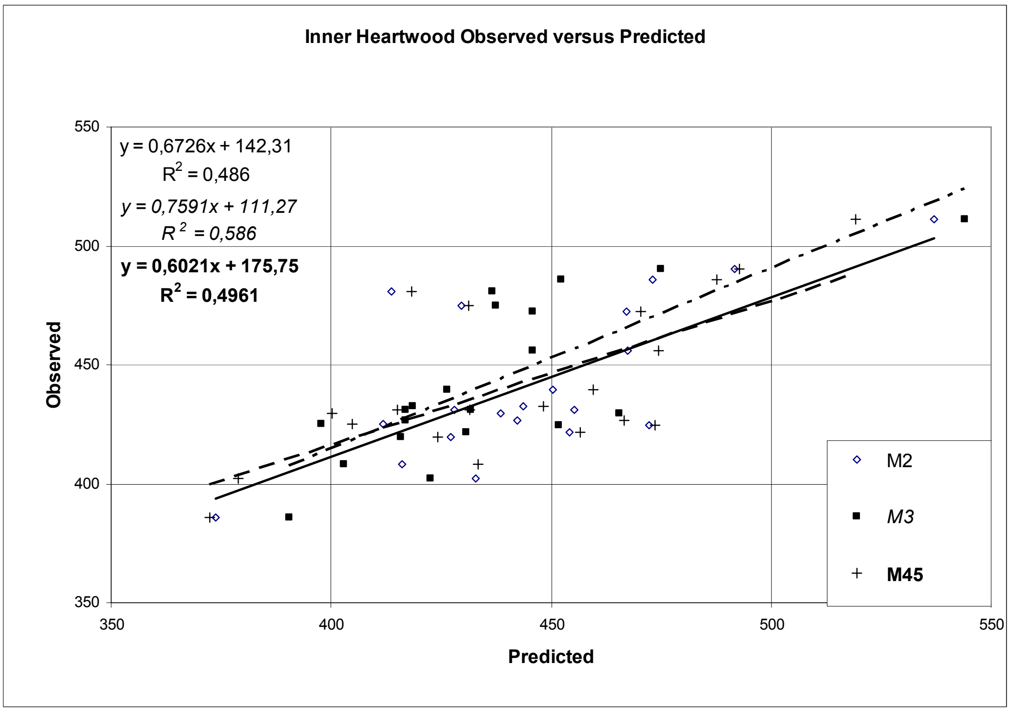

Figure 20. Derived models applied to an area measured as the average of a box containing the inner heartwood. Same area is measured in both green and dry state. Annual ring width included in Model 45 measured only as the first 20 annual rings.

Discussion

The ultimate goal with this study was to be able to create and verify a dry density model for global use. From this study I have learned that such a goal is not impossible to reach but if higher precision of the model is required local models must be made. In the following I will discuss some things to learn from this study.

Sources of Inaccuracy

Since three different data sets have been used in this study, several questions regarding how well the result from applying models to the different sets could be compared. The differences gave a good hint of the abilities of the models and how to make more precise industrial models in the future.

By using average data for modelling (Tamminen data) some noise may have been avoided, the risk is though that some covariance may be hidden and impossible for the algorithm to find. Some of the unused variables in the final multivariate model can still contain relevant variation which could be utilized in an industrial model.

How well the relatively few discs of the SMP data can represent the complete sample is not studied. All in all the sample consisted of 1733 discs and the fewest number of discs the models were applied to was 43, due to the simple algorithm for finding the correct heartwood radius. These discs were in that sense picked in a random way which still makes the validation acceptable. It is also a question how well the whole sample disc dry density correspond to the dry heartwood density.

The moisture content of the Finnish sample was not corrected by any way to get an estimation of the dry density. The reason was to not add another source of inaccuracy to the study. Instead an underestimation of the density is assumed, which proved to be the case since all models are offset to the positive side and the slope of the regression line is lower than one.

In the Finnish sample the estimated position in the log and the annual ring width caused some concern. The pattern in applying the models to this data was that the model considering the longitudinal position in the stem was the worst one while all single variable models were better. The position in the stem was quite roughly estimated, as the tree height, which might explain this phenomenon. The annual ring width was based on the twenty innermost annual rings, which, together with the height estimation caused Model 45 to be roughly unusable for prediction. This gives a hint of the difficulties of using variables that are difficult to measure for the prediction.

Position to Measure on the Log

Many things could be learned from the literature study. Some of the results in this study confirm different theories or results found in literature. One such was the best position from where to assess information. A preferred measurement position (Figure 21) for each log would be in the butt end of all logs except for the first log, in which the measurement would become better if measured in the top of the log. By using that position unwanted effects of deviant moisture content can be avoided while the largest area of interest and easiest position to define is utilized. The easiest way of defining one measurement position, to base the prediction on for industrial use, would be the middle of each log.

This would still not exclude the risk of overestimating density from intermediate wood areas but the other unwanted moisture deviations would be avoided, as well as the dehydrated ends of each log.

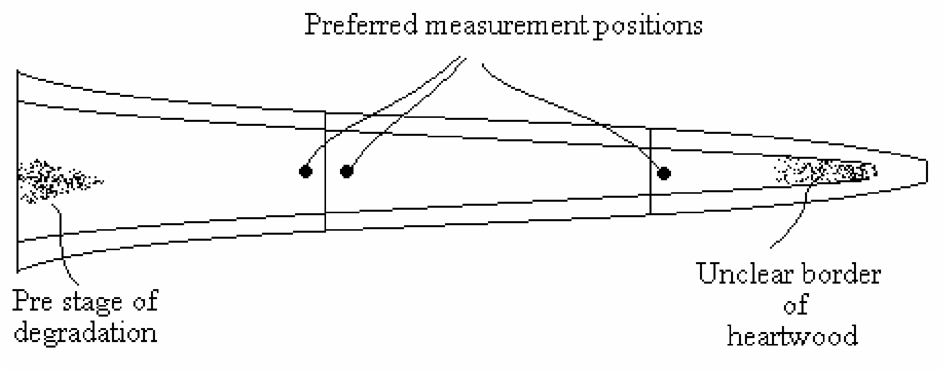

Figure 21. A schematic view of a stem and the preferred measurement positions.

Radial Position and Size of the Measured Area

Although not a variable used in the initial modelling it was found that some kind of variable defining the green radial density variation should be tried to further improve models or to make them less sensitive to the final cross sectional area of interest. The whole idea of pre-sorting is that you should be able to define any possible end use, not sorting with only one in mind.

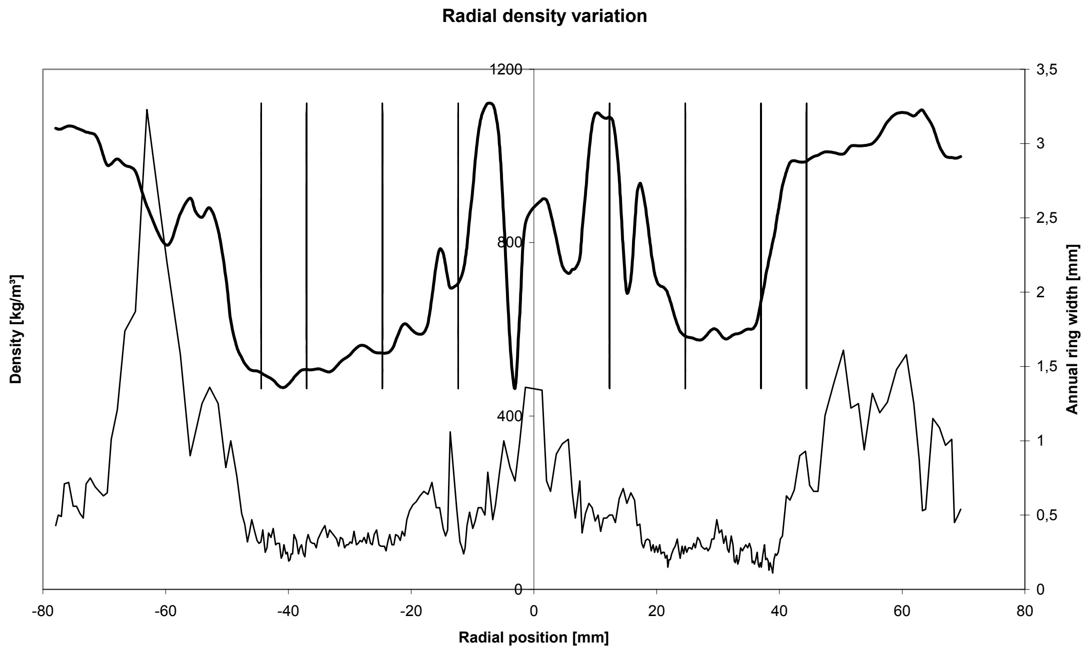

Figure 22. The radial density variation and annual ring width of one disc in the SMP data base. The different regions examined are marked, from origo at 25, 50, 75 and 90 % heartwood share. The sample disc is acquired from 32 % relative position in the stem.

It can clearly be seen that the radial variation is important to consider when using green density to predict the dry density (Figure 22). The risk of including sapwood density in the measurement gets bigger the closer to the estimated heartwood border you get. The example in the figure is the worst, thus shows the problem best.

By using 25 % heartwood share the higher density of the juvenile wood protrudes, in this example a very high density assessment with an accompanied high prediction value. Compare the average density of that area with the one in the region 50-75 % and the result will be much different.

For the Finnish sample the dry density could be measured from the same area as the green density. This made the prediction more stable and not dependent on the area used for prediction in the same way as in the SMP data (Table 6). This is only valid for the models applied to data gathered at the measurement position, which was not the case with Model 45. A conclusion could be that the true variation in accuracy for the validation on the SMP-data does not depend as much on the area measured as on what area the reference value was based on.

On one hand this means that the models should always be applied to the area of interest in the specific sawing pattern, as long as it is so small that the sapwood will not be included. On the other hand it also shows how little the variation in the juvenile wood says about the whole cross sectional volume of the stem.

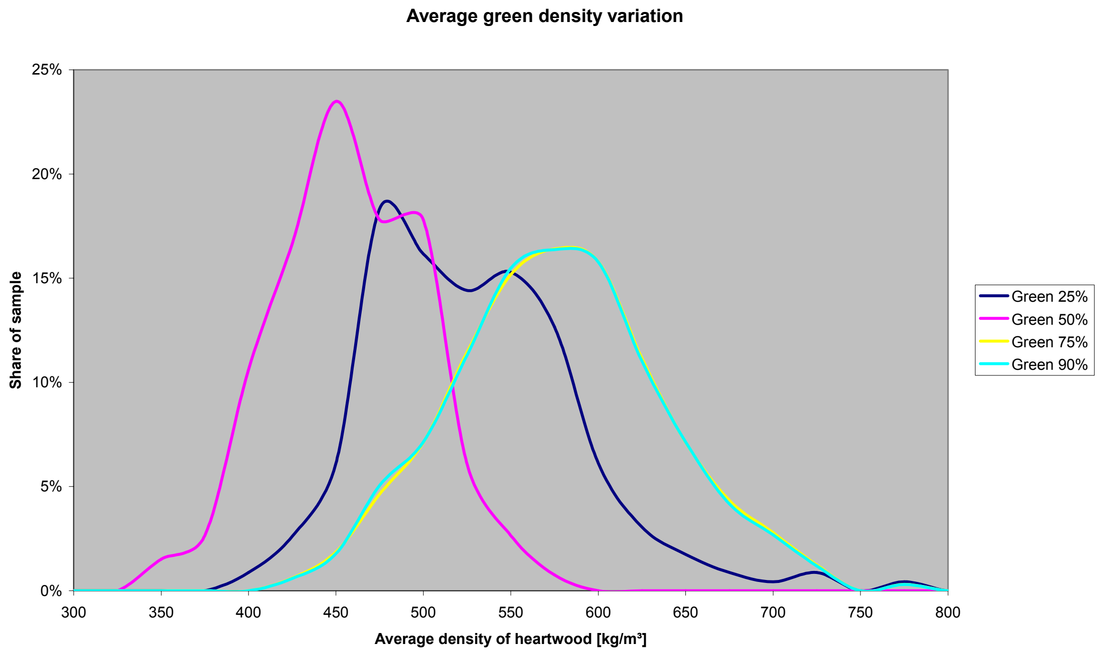

Figure 23. The average density variation for different radius groups (SMP-data).

Although varying number of observations between the radius classes it seems as if the distribution of 75 % heartwood area share and the 90 % heartwood area share are similar (Figure 23). When looking at individual density measurements and the fit of the model (Table 3, Table 4) for each of these classes the 75 % level is certainly to prefer. By using this share as base for the calculation the risk of including sapwood is reduced, while retaining as big base as possible for the calculation.

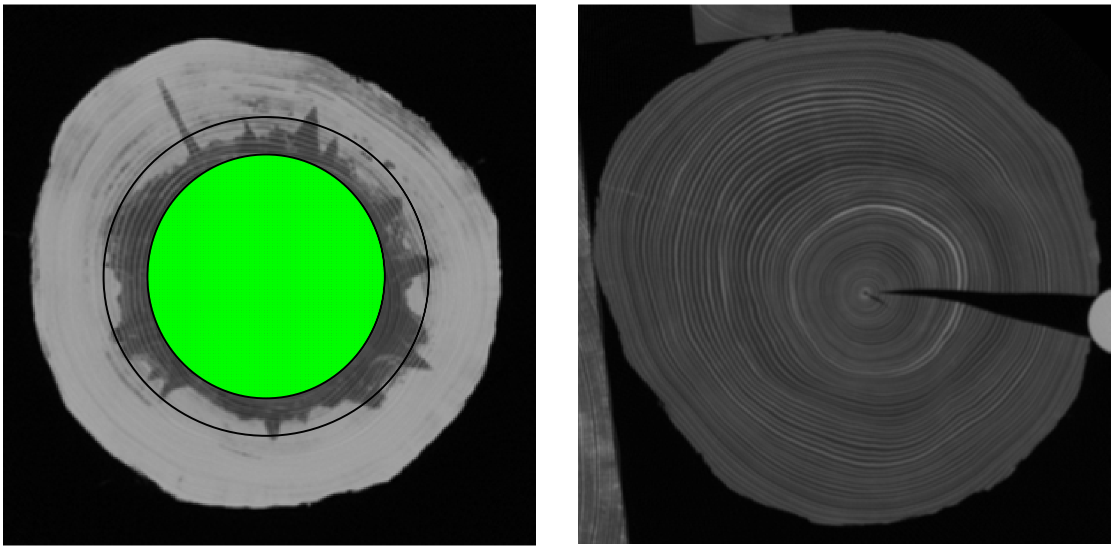

Figure 24. A schematic view of the 75 % and 90 % heartwood area share on the green log, compared to the dry disc from the same log (not equal scale). Radial variation is difficult to consider. (Finnish sample material.)

In this study no good variables are given to consider the radial variation (Figure 24). The average annual ring width would, in this extreme case (Figure 22), perhaps give a better estimation but the variation is still several hundred percent within the heartwood. Of course this requires the measurement to be done at the position of prediction.

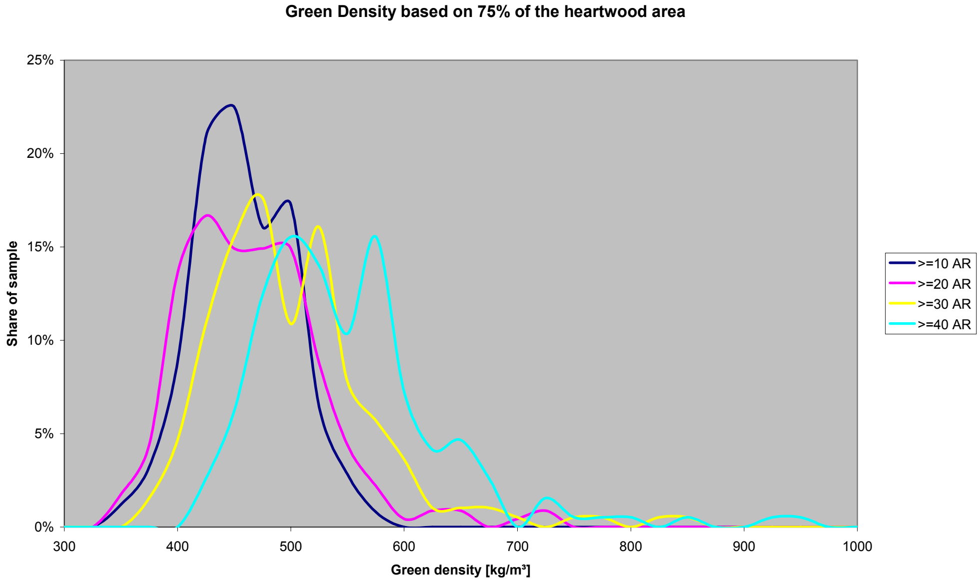

Figure 25. The distribution of green density within the measurement based on 75 % of the heartwood area, divided into the least number of annual rings the measurement is based on (SMP-data).

When studying how well the models can predict the dry density depending on the age (by judging from diameter), the model considering position in the tree as one variable (Model 2) gives a slight advance in most cases (Table 3, Table 4 and Table 5). Although the best, the correlation of the model is still so weak that the implementation of it, based only at the share of heartwood, will not be possible.

When considering the models applied on data sorted on number of annual rings, the M2 is still the best model. The correlation increases with the number of annual rings included, more than with the share of heartwood included. This depends mostly on the limitation of the number of cases where only a few annual rings are forming the base for predicting the density of a whole disc. Although the main body of discs has a diameter of about 200 mm, the 150 mm discs are exchanged for the double diameter in the ≥40 annual ring case (Figure 26).

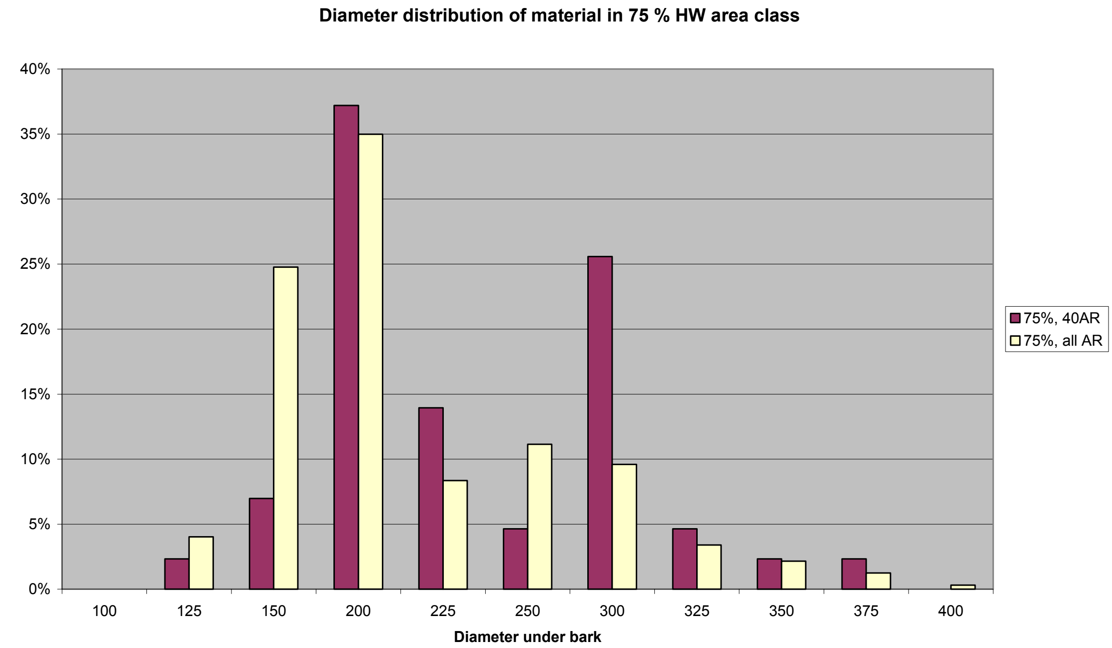

Figure 26. Diameter distribution of the 75 % heartwood area sample discs (SMP-data).

The observations made on the Tamminen material is also verified in that sense that the inner heartwood for smaller logs (25 % HW) gives a slightly better prediction then when including 50 % of the area, meaning that the juvenile wood might give a better average value of the radial variation than the mature wood for smaller logs.

For larger logs the prediction increases with the amount of correctly classified heartwood, in all cases the correlation is better then when only filtering on the amount of heartwood. This can be explained by that the observations with the smallest number of annual rings constituting the heartwood are filtered away and the base for an average value is enlarged.

The Effect of Moisture Content

Since both the EN384 and the Equation 6 models were applied by deliberately underestimating the moisture content the effect of heartwood moisture content could be examined to some extent. Although the density dependent shrinkage was applied from Equation 1, inherited by Equation 6, the relation was not good enough to compensate for the effect of underestimating the density of high density specimens (Figure 18). The slope of the regression line was about 0.5 in both cases which was not very different from that between uncorrected green heartwood and dry heartwood. This calls for further explanatory variables than only moisture content and shrinkage. Further proof for this theory was the better fit of the model considering also position in the stem (Model 2). To fully understand the effect of moisture content, and the possibility to correct the green density from a moisture content value, a separate study is required.

Conclusions

Models for dry density prediction from green log measured parameters can be made with the green density as the strongest variable. Other variables can also be added to increase the explanatory ability of the model, like the longitudinal position in the stem and annual ring width.

Multivariate calibrated models gives better predictions than both mathematically derived models and correction models proposed in standards. Partly due to the big moisture content range, partly due to the difficulty to relate shrinkage and moisture loss to annual ring width and density.

A general Swedish model is validated with Finnish material, with an R^2 of 60 % and prediction error of 27 kg/m^3.This is a result which should be possible to reproduce with industrial equipment in a saw mill. When considering regional or mill specific models, the model R^2 of 78 % on the test set is promising in that sense that the regional variation is more homogenous, which would make the prediction more accurate.

From a practical point of view it is important to consider the radial variation in that sense that the cross sectional area of interest for the end product is the one measured as far as possible. The share of heartwood included in the measurement must be as large as possible without including any sapwood, if the whole cross section density is of interest. At the same time, possibly dehydrated, degraded or undefined heartwood areas should be avoided by only performing the measurement in the middle part of the log.

Pre-grading of logs by density gives a possibility for sawmills to increase the value recovery of sawn products intended for joinery- as well as construction purposes. Customer expectations and standard requirements can be met with a minimum of losses in the process, compared to grading saw falling material.

Future work

Some ideas of how to further examine the ability to predict the dry density of green logs are:

1. It should be found out how well the industrially measured features correspond to the laboratory measured ones presented in this report and further evaluations should be based on industrial measurements in order to speed up the development process.
2. Other variables could be introduced in the modelling. Especially such that would in some way explain the radial density variation. This could be made as measurement of properties related to the radial variation, such as distance between whorls as a parameter related to annual ring width.
3. Individual data should be used in future modelling, not average data, although the method showed some potential.
4. The dataset should be expanded for each sawmill that will use a density pre-grading process. Regional variation could then be taken into account and models built for a specific area. Pine should also be included in an expanded industrial trial.

A suitable way of making mill specific models would be to gather information from an X-ray log scanner and combine those measurements with the simple average density measurement of sawn and dried boards. An option is to use the CT-scanner values as reference values for both dried and green logs.

For the cause of strength grading a direct prediction on the base of industrially measurable parameters seems to be more realistic as a pre-grading method, compared to a pure pre-grading based on the density prediction.

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