LICENTIATE THESIS

# Moisture Content Measurement in the Wood Industry

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## Abstract

In the wood industry, determination of the moisture content (mc) with a high accuracy is of great importance. The green mc is important for optimisation of the wood drying process at sawmills, whereas the mc of dried boards is of interest for the further processing and final use of the boards. In the first publication in this thesis, which is a technical report written in Swedish, different measuring techniques with their own pros and cons are discussed. A total of 13 different measurement principles are discussed, focusing on the ability to measure mc in the range of 7-18%. The result suggests that mc-meters that use electromagnetic waves in the radio- and microwave ranges have the greatest potential to become the next generation mc-meters for dried boards.

The second publication, which is presented in this thesis, investigates the possibility of measuring the green sapwood mc in pine logs by combining industrial X-ray scanners and 3D-scanners. The method is shown to be suitable for identifying batches of logs in which the sapwood has begun to dry prior to sawing, rather than predicting the sapwood mc with high accuracy at the level of individual logs.

In a single board, one would ideally like to measure the mc profile over the entire cross section to determine the mc gradient. However, the measured result is affected in the vicinity of the board edges. In the third publication, the existence of this problem is identified, and it is shown that it can be decreased by using correlation functions generated by finite element simulations of the measurement system.

The fourth publication considers the potential to increase the measurement accuracy of the mc of single boards by combining different measurement techniques. Microwaves, X-rays and visual sorting into different wood quality classes are used. It is shown that the measurement accuracy is increased by the addition of both the X-ray measurements and the visual sorting. This result is interesting because visual sorting is usually already present in the final sorting of large sawmills. This is also where the mc measurement preferably is to be performed.

**Keywords:** edge effects, final sorting, green sorting, mc, microwaves, sawmill, wood quality, X-rays.

## Preface

The work presented in the following pages was performed at the wood technology department of SP Technical Research Institute of Sweden, SP Trä Skellefteå, in close collaboration with the Division of Wood Physics at Luleå University of Technology. I would like to express my warmest gratitude to my present and past co-workers for all the joy and profession we have shared. I honestly appreciate the work of my former supervisors, Jonas Danvind, Lena Antti and Johan Oja (who became so fed up with me that they quit their work?). I would also like to express my sincere gratitude to my present supervisors, Lars Hansson and Tom Morén, who stayed to the bitter end of my licentiate work. All collaboration with industrial partners; Holmen Timber AB, Martinsons Såg AB, MiCROTEC GmbH/srl, SCA Timber AB, Stora Enso Timber AB and Valutec AB throughout the work has also been greatly appreciated – you represent the greatest allurement for me to ever finish my PhD.

This work was also generously supported by the Swedish Governmental Agency for Innovation Systems (Vinnova), WoodCenter North (TCN) and SP Technical Research Institute of Sweden.

Last, but not least, I would like to send a big hug to everyone who is supporting me as a person.

Skellefteå, March 2012

Tommy Vikberg

## List of publications

I. Vikberg, T. (2010) Fuktkvotsmätare för träindustrin – En kartläggning av metoder för mätning av fuktkvoter i intervallet 7-18 fuktkvotsprocent. Technical report, *Luleå University of Technology*, ISBN: 978-91-7439-198-5. (*In Swedish*).

II. Skog, J. Vikberg, T. & Oja, J. (2010). Sapwood moisture-content measurements in Pinus sylvestris sawlogs combining X-ray and three-dimensional scanning. *Wood Material Science and Engineering*, 5(2): 91-96.

III. Vikberg T, Hansson L, Schajer GS, Oja J (2012). Effects on microwave measurements and simulations when collecting data close to edges of wooden boards. *Measurement* 45(3): 525-528.

IV. Vikberg, T. Oja, J. & Antti, L. (2011). Moisture content measurement in Scots pine by microwave and X-rays. Submitted to *Journal of Wood and Fiber Science*.

## Contents

## Introduction

Wood is a natural material with properties that vary greatly, even within a single board (Dinwoodie 2000). Parameters such as knots, grain angles, resin content, lignin content, and cell wall thickness all affect the parameters of interest for end users, such as durability, strength, and dimension stability.

This work focus on one important parameter to know throughout the whole process from the forest to the finalised wood product, as well as in the final application of the wood, namely the moisture content (mc).

In the processes at a sawmill, knowledge of the mc of the green wood is valuable because it affects the required drying time in the capillary phase and consequently, the logistics and the optimal usage of the boiler (Esping 1988). One way to obtain an mc signal when the fibre saturation point (fsp) is approached in the ongoing kiln drying process is to examine the required heat and ventilation to maintain the designated climate in the kiln. This method is called adaptive control, and it is already implemented in some kiln control systems (Larsson et al. 2002). An increasingly common approach to predicting the outcome of the wood drying process is the use of simulation programs. It is well known that simulations cannot perform well if the model itself is bad or if the ingoing model parameters are not well known. Therefore, measuring parameters such as the total wood volume in a kiln, the wood density and the mc prior to drying are important, both to achieve good predictions of the outcome and to develop the model itself.

Determination of the wood density and the mc of the sawn green boards is difficult with the high production speeds in a modern sawmill. These difficulties originate in problems with the distinction between water and wood.

To determine the mc with high accuracy at the final sorting, prior to the shipping of the sawn and dried wood to the final customers, is important to enable the ensurance of the end products quality. A well-defined mc is a valuable tool for prediction of the performance of the wood in a final application, and the status of wood as an engineering material would improve if sawmills were able to ensure a certain distribution of the boards mc in a batch. By combining an mc measurement with high accuracy in the final sorting and a system for tracking the wood throughout the process (Flodin 2008; Uusijärvi et al. 2010), it would also be possible to gain a lot of knowledge of the production steps prior to the final sorting. Almost all boards produced at Swedish sawmills are dried in kilns. If one tries to reach an average mc as fast as possible with only the absence of cracks and colour changes as quality factors, a large mc variation is produced between the boards in a single batch, and

large mc gradients are present within each individual board. If, for example, the board is to be split into two boards and used as a panel, the mc gradient is an important quality factor because the later mc equalisation throughout the board, along with the release of internal stresses, will cause warping.

There have been (and still are) many different methods to predict the mc of dried boards. The majority of these devices use electromagnetic (EM) waves of some certain wavelength to estimate the mc. The most common of such devices in Swedish sawmills is the capacitive mc meter. Capacitive meters are fast and non-contacting, but they are not very accurate (Esping 2003). In more recent years, mc meters that use higher measuring frequencies have become more commonly used in the sawmill industry, and their potential to measure the mc with higher accuracy than that of capacitive meters has been shown (Nilsson 2010). Higher frequencies introduce new problems that must be taken into account when developing, calibrating and evaluating measuring devices. One problem that is commonly addressed is the occurrence of phase shifts that exceed multiples of $2\pi$ (Hansson et al. 2006). This problem can be solved by tracking the phase when the board enters the EM field, using two or more measurement frequencies or examining the ratio between the parallel- and cross-fibre phase angles with two polarisations of the EM field (Schajer and Orhan 2005). Another problem is caused by the scattering of the EM field when measurements take place in the vicinity of edges of the material under testing (Meixner 1972). Because the boards are usually cross-fed through the final sorting station (i.e., the timeslot for one board to pass a measuring head is short) and there is a wish of measuring the moisture gradients, there is a demand for measurements that can be taken close to the board edges.

Understanding the behaviour of EM waves is difficult because they are not visible. Simulation by the finite element method (FEM) has been shown to be a valuable tool for understanding the interaction between the tested material, its surroundings and the measuring device itself (Lundgren et al. 2006; Sjöden 2008).

## Aim

The accuracy of the mc measurements considered in this work was defined in two ways, according intended use of the result in the later production steps. For the green sapwood mc measured by combining industrial X-ray log scanners and 3D-scanners, which are already present at some of the larger sawmills, the aim was to investigate the potential to identify populations of logs in which the sapwood had begun to dry before entering the sawmill.

For the mc measurement of dried single boards, the aim was to develop or refine a method or device to obtain the average mc in the measured volume of wood within ±1% mc for 90% of the measurements in the designated range of 7-18% mc.

## Theory

The mc of wood is defined as the ratio between the water mass and the oven-dry wood mass in a certain volume of wood, see equation (1).

$$u = \frac{m_u - m_0}{m_0} \tag{1}$$

where $u$ is the mc, $m$ is the mass and the subscript indicates the mc. The oven-dry method is used to provide a reference mc value. In this method, a wood sample is weighed before and immediately after its placement in a well-ventilated oven at 103±2℃ until the change in mass is less than 0.1% between two measurements separated by an interval of two hours. A full description of the oven-dry method can be found in the standard SS-EN 13183-1. Water in the wood can either be found as free water in the lumen or water bound within the cell walls (Esping 1992; Morén 2007). Because the water in the lumen requires less energy to leave the wood compared to the water in the cell walls, one can assume that the lumen is emptied before the bound water in the cell walls begins to leave the wood. The point at which there is no water in the lumen but the cell walls remain fully saturated is called the fsp, and it is usually reported to occur within the mc range of 27-30% at room temperature (Dinwoodie 2000; Esping 1992; Kollman and Côté 1968; Morén 2007). A principal sketch of water in wood can be seen in Figure 1.

*Figure 1. Schematic picture of water in a wood cell. To the left is a fully saturated cell, in which the entire lumen is filled with water. In the centre is a cell at the fibre saturation point, at which the lumen is empty but the cell wall remains fully saturated. To the right is a cell at a moisture content value below the fibre saturation point, at which the cell wall also contains less water and has started to shrink.*

When a tree grows, the actual growth takes place in the cambium, which is located between the xylem and phloem, see Figure 2.

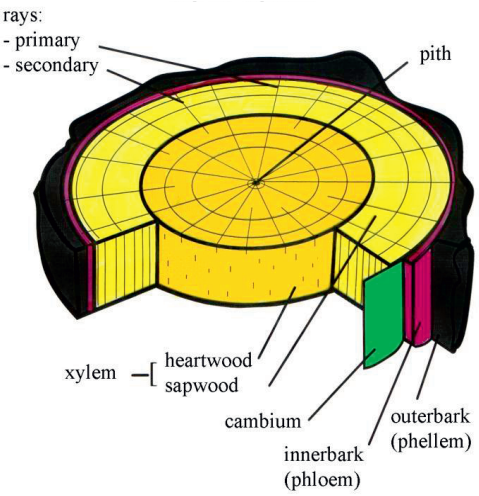


*Figure 2. Cross section of stem. Reprinted with permission from Margot Sehlstedt-Persson.*

Through cell division, the bark grows outwards from the cambium, and the xylem grows inwards. In the first part of the growing season, the tracheids (wood cells) have a large lumen and thin cell walls compared to the late-season tracheids. The difference in the structure of the tracheids is known as annual rings, which are shown in Figure 3.

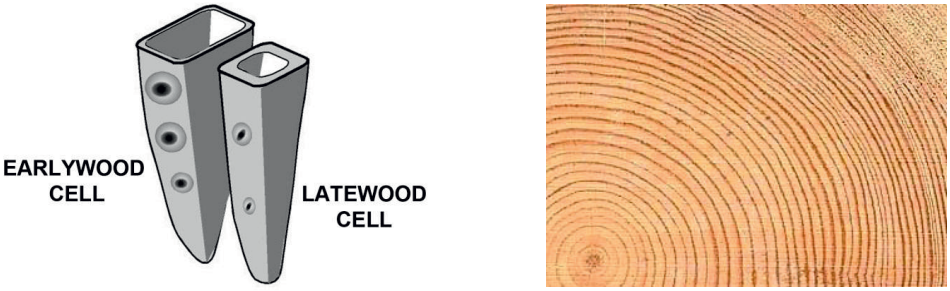


*Figure 3. Earlywood and latewood tracheids (left) and annual rings of Scots pine (right).*

Because a tree grows both in height and dimension each year, one can think of the growth as stacking cones on top of each other. When the tree grows older, there is no longer a need for the tree to use the entire stem for water and nutrient transportation, and heartwood begins to develop. Because heartwood in a growing tree is not active in water transportation, the mc in green heartwood is much lower and less variable than the green sapwood mc. If a log contains a fraction of heartwood and the raw density profile is measured through the log, one can assume a relation between the heartwood and sapwood density (Tamminen 1962) and fix the mc in the heartwood (Esping 1992), allowing estimation of the mc in the green sapwood.

One way to determine the density profile of a log is by use of an X-ray log scanner (Grundberg 1999). The attenuation of a monochromatic EM wave passing through a material is described by the following expression:

$$I = I_0 e^{-\mu X} \tag{2}$$

where $I_0$ is the incident intensity, $\mu$ is the attenuation constant and $X$ is the thickness of the material. The attenuation constant $\mu$ can be considered to be a function of the attenuation of both the dry wood and water (i.e., $\mu = \mu(wood, water)$). When a density profile is determined, the relation between the density at a certain mc and the dry density can be used, as shown in equation (3).

$$\rho_{u,u} = \frac{m_u}{V_u} = \frac{(1+u)m_0}{(1+\alpha_u)V_0} = \frac{(1+u)}{(1+\alpha_u)}\rho_{0,0} \tag{3}$$

where $\rho$ is the density, $m$ is the mass, $V$ is the volume, $\alpha$ is the volumetric swelling coefficient and the subscript indicates the mc. If the swelling of the wood is assumed to be linear between an mc of 0% and the fsp, the volumetric swelling coefficient can be calculated as follows:

$$\alpha_u = \begin{cases} \dfrac{\alpha_{max} u}{u_{fsp}}, u < u_{fsp} \\ \alpha_{max}, u \geq u_{fsp}. \end{cases} \tag{4}$$

If the dry density is known and the mc is assumed to be above the fsp (i.e., $\alpha_u = \alpha_{max}$), the mc can be extracted from equation (3), as follows:

$$u = \frac{(1+\alpha_{max})\rho_{u,u}}{\rho_{0,0}} - 1. \tag{5}$$

In a growing tree, one usually considers three main directions: radial, tangential and longitudinal (see Figure 4).

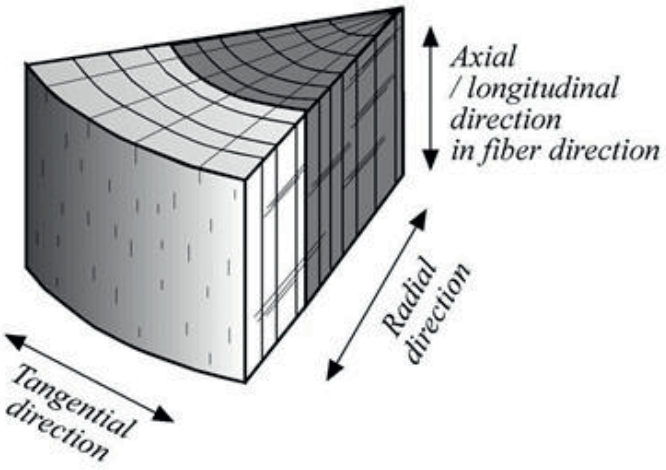


*Figure 4. Main directions in wood. Reprinted with permission from Margot Sehlstedt-Persson.*

In clear wood, the wood fibres are mainly directed in the longitudinal direction, although some deviation in the grain direction is always present (especially in the vicinity of knots and top ruptures). The grain angle on a wood surface can be found by using the tracheid effect (Oja et al. 2006), or more as an average in a board by using microwaves (Schajer and Orhan 2006). When using microwaves to detect the grain angle, the difference in the size of the dielectric constant as a function of the wood direction is used. From a mathematical perspective, it is practical to represent the dielectric constant as a complex tensor, as follows:

$$\boldsymbol{\varepsilon}^* = \boldsymbol{\varepsilon}' - i\boldsymbol{\varepsilon}'' \tag{6}$$

where $\boldsymbol{\varepsilon}'$ is the relative dielectric constant tensor (real part) and $\boldsymbol{\varepsilon}''$ is the dielectric loss factor tensor (imaginary part). Torgovnikov (1993) stated that the dielectric properties of wood are not generally believed to change if an applied EM field is rotated 180˚. The difference in the dielectric properties between the tangential and radial directions is also negligible; therefore, a common simplification is to use the dielectric constants of the parallel and cross grain directions, as shown in equation (7)

$$\boldsymbol{\varepsilon}' = \begin{vmatrix} \varepsilon'_{RR} & \varepsilon'_{RT} & \varepsilon'_{RL} \\ \varepsilon'_{TR} & \varepsilon'_{TT} & \varepsilon'_{TL} \\ \varepsilon'_{LR} & \varepsilon'_{LT} & \varepsilon'_{LL} \end{vmatrix} \approx \begin{vmatrix} \varepsilon'_{\perp} & 0 & 0 \\ 0 & \varepsilon'_{\perp} & 0 \\ 0 & 0 & \varepsilon'_{||} \end{vmatrix}. \tag{7}$$

The directional dependence of the dielectric constant affects the polarisation of an incoming EM wave with a polarisation other than one of the principal directions of the wood (i.e., the parallel or cross grain direction). For small deviations between the

incoming polarisation and the principal direction in the wood the polarisation is, however negligible (Schajer and Orhan 2005). In addition to the direction in the wood, the dielectric constant is also dependent on the frequency, mc, dry density and temperature (Torgovnikov 1993).

When an EM wave travels in a dielectric medium other than vacuum, it always experiences some losses (i.e., $\boldsymbol{\varepsilon}^*_{vacuum} \equiv 1 \neq \boldsymbol{\varepsilon}^*_{medium}$). The strength of the EM field follows equation (2), and a phase shift $\phi$ occurs because the propagation speed of the EM wave is lower in the material than in vacuum, as shown in Figure 5.

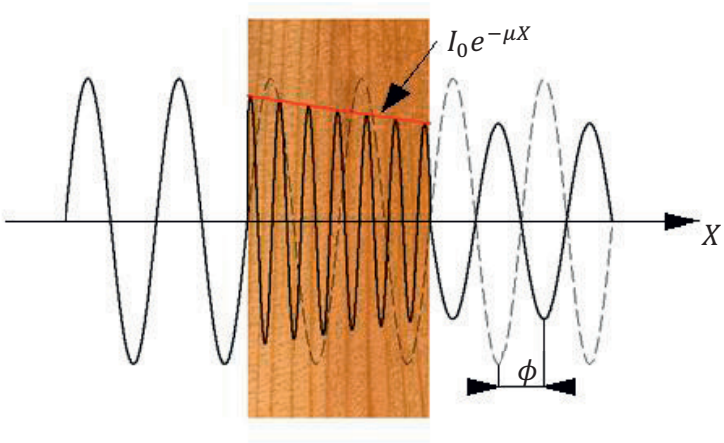


*Figure 5. Attenuation and phase shift of an electromagnetic wave as it travels through wood. Reprinted with permission from Lars Hansson.*

The many factors that affect the attenuation and phase shift, which are the two quantities that can be measured, must be considered when one is working with microwave devices to correctly determine the accuracy of the device.

## Publication I

### *Material and Methods*

A literature survey served as the basis of the "state of the art" investigation, which resulted in the first publication. To avoid overlooking any technique with the potential to measure the mc with high accuracy, all possible techniques mentioned by people in the topic area, as well as all techniques found in the literature, were considered, producing a total of 13 different techniques that were examined. The work focused on finding either a commercial product or a measurement technique that could be developed further. The main goal was prediction of the mc in the range of 7-18% mc.

### *Results and discussion*

**Resistive meters** measure the resistance between two electrodes that are hammered into the wood. This method is cheap, easily applicable and not sensitive to the surrounding environment, which also makes the method useful inside drying kilns. The disadvantage of the method is that the resistance in the wood is affected by the wood temperature, its content of salts and extractives and the design of the electrodes. In an extensive test of hand held resistive mc meters, the variability of the resistance itself caused 90% of the measurements to fall within the interval of $\pm$1% mc for Nordic pine and $\pm$0.8% mc for Nordic spruce. However, when resistive mc meters were used in an industrial test, it was concluded that only 60% of the readings could be expected to be within $\pm$1% mc from the oven-dry reference in practice (Forsén and Tarvainen 2000).

**Capacitive mc meters** measure the capacitance of the wood, which is related to the dielectric constant, and it is thereby dependent on the temperature, density and mc of the wood (Torgovnikov 1993). Capacitive meters are fast and non-contacting, but they are not very accurate. In an industrial test of capacitive inline mc meters, the mc of 90% of the individual boards was measured within $\pm$2.4% mc from the oven-dry reference (Esping 2003). Capacitive mc meters also exist as hand held devices, for which it has been shown that a planed surface provides an mc prediction that is 1% mc higher than that of a sawn wood surface (Garrahan and Lavoie 2005). Two industrial tests in which capacitive mc meters were used inside a drying kiln to predict the mc showed high levels of noise. In these tests, the widths of the intervals containing 90% of the individual measurements were $\pm$2.4 and $\pm$1.3% mc (Fløtaker and Trondstad 2000).

High frequency EM waves, such as **γ- and X-rays,** easily penetrate both green and dry wood. However, it is not possible to distinguish between wood and water with a single measurement (Tiitta et al. 1993).

By using **Near Infra-Red**, NIR, a spectrum with the vibrational energies of the molecules inside a material can be determined. Calibrations can be performed with respect to the water content, temperature, fibre angle, surface roughness, amount of extractives, etc. (Tsuchikawa 2007). In addition to the complexity of correctly interpreting the spectra, NIR measurements on solid wood are always shallow; consequently, the result is not representative of the whole board.

The frequency of **microwaves** allows dipolar molecules like water to align (at least partly) with the EM field when it changes direction. The alignment of the molecules inside the material requires energy, which can be measured as an attenuation of the EM field. The attenuation and phase shift depend on the frequency, the dry wood density, the mc, the temperature, and the wood fibre direction (Torgovnikov 1993). The absolute difference in the signal strength per percent mc decreases as the mc decreases (Schajer and Orhan 2006) and depending on the setup, there can be a lower limit of the mc that can be measured. Additionally, when the amount of water per unit area is large, problems caused by the great attenuation can impede measurement of the mc. Therefore, microwave mc meters are most useful at the final sorting at sawmills, where most boards are found within the mc range of 7-20%. An investigation of a system's ability to predict the mc values of hemlock and Douglas fir in the mc range of 7-28% determined that the intervals containing 90% of the errors had widths of ±2.0 and 2.6% mc, respectively (Schajer and Orhan 2006). In a recent test of an industrial device, conditioned pieces of wood, divided into groups of approximately 20 pieces in each group according to their quality and mc range were measured. The test provided intervals containing 90% of the errors that were ±0.5-1.0% mc wide (Nilsson 2010).

**Radio waves** have longer wavelengths than microwaves. As a result, their spatial resolution is lower, and the signal can be considered to be filtered. When an industrial device using radio waves was subjected to the same test as described above, the resulting intervals containing 90% of the errors had widths of ±0.7-1.8% mc (Nilsson 2010).

**Nuclear Magnetic Resonance** (NMR) tilts the atomic spin axis in a material by applying an external magnetic field. After the external magnetic field is switched off,

the atomic spin returns to its original direction, and a measureable signal is created. The mc can be predicted with very high accuracy (Bucur 2003; Merela 2009; Prado 2001), but the time required to tilt the spin is too high to allow online implementation of this solution.

**Ultrasound** can be measured either as reflected or transmitted wave, but tests have shown that the accuracy of such mc measurements is low (Vun et al. 2008).

Measuring the **mass** of the wood is simple, and robust systems are available. Four industrial tests were conducted, in which load cells were installed inside a kiln to measure the total mass of a stack. This value was used to measure the final mc, producing absolute errors of 0.3, 4.9, 10.0 and 11.2% mc (Fløtaker and Trondstad 2000). To achieve an mc measurement, either the dry wood mass or the mass of water must be known at some point. Measuring the mass may provide a good complement to another measuring technique.

Because wood shrinks when it is dried below the fsp, the mc can be determined by measuring the **shrinkage** of the boards. Because the shrinkage varies between individual boards (Hájek and Esping 1996), the method is not applicable to single boards. Industrial tests have been performed in which the shrinkage of an entire stack has been measured during drying. In these tests, problems caused by the shrinkage of stickers, board cupping and twisting have been noticed (Fløtaker and Trondstad 2000). Optical systems for measuring only board shrinkage are discussed, but they suffer drawbacks as a result of the representativeness of the outer board edges in the stack and the harsh environment for the measuring device.

By using a **neutron source,** the hydrogen concentration of a material can be estimated. Because the mass concentration of hydrogen differs between dry wood and water, the measurement can be used to estimate the mc if the mass is known at some point. A test to measure the mc inside a drying kiln by lowering a neutron source and detector into the floor, as described by Fløtaker and Trondstad (2000), seems promising, but it is stated that the geometry of the stack is of high importance. With the described setup, the neutrons are spread in a half sphere, which increases in radius as the wood dries. Consequently, the volume of wood that is actually measured and the representativeness of the measurement for the whole batch are debatable. Individual measurements also show great variation; therefore, the method is most likely not applicable for inline measurement of single boards when the measurement speed is important.

A **time domain reflectometer** sends an EM pulse and measures the reflected amplitude as a function of time. The working principle can be compared to that of ultrasound. Applied to wood, the only references that have been found measure the moisture density of living trees rather than the mc of dried lumber (Constantz and Murphy 1990; Wullschleger et al. 1996).

Despite the number of methods that have been applied to mc measurements throughout the years, none of them has proven to be completely successful. Consequently, combining different measuring devices and their results with traceability throughout the production chain would most likely be a fast and easy way to improve the overall quality of the mc prediction, if not of the mc measurement itself.

## Publication II

### *Material and Methods*

The measurement of green sapwood mc and sorting of logs into groups with high and low green sapwood mc by means the combination of an industrial X-ray log scanner and a 3D- scanner was investigated. The Swedish stem bank for pine logs (Grundberg et al. 1995) served as a source of material for the work. In short, the stem bank consists of computer tomography (CT) images of full-size green logs. These images were taken at distances of 4 cm where the wood was free of knots and distances of 1 cm in knot whirls. There are a total of 560 logs in the pine stem bank, of which 165 logs are butt logs. As a complement to the green logs, the stem bank also consists of CT images of discs taken from the butt end of each log and conditioned to 9% mc.

*Calculation of reference values*

The dry sapwood density was calculated by extracting $\rho_{0,0}$ from equation (3) and using density measurements of the conditioned wood discs. To determine the green mc that was used as a reference, measurements of the green sapwood density of each log were also performed on clean wood at an approximate distance of 400 mm from the butt end. The reference mc was then calculated according to equation (5). To make the calculations, the following assumptions were applied: the conditioned disks were assumed to have exactly 9% mc, the maximum volumetric swelling coefficient was taken to be 14.2% (Esping 1992), the fsp was assumed to be 28% (Kollman and Côté 1968) and a linear relation was assumed between the dry density of the sapwood in the butt end and the dry density 400 mm from the butt end.

*Calculation of prediction values*

The sapwood mc was predicted by simulating industrial X-ray and 3D data from the stem bank. The simulation method is described by Skog and Oja (2010). From the simulations, both the green sapwood and the green heartwood density were calculated at a distance of 400 mm from the butt end of each log. With the assumption that the mc was fixed in the heartwood (Esping 1992) and that a relationship existed between the dry heartwood and dry sapwood density, models for prediction of the sapwood mc were developed. Because of the greater amount of extractives in the butt logs compared to those of the upper logs (Tamminen 1962), two separate models were developed.

## *Results and discussion*

Because the stem bank does not contain any logs that exhibit significant drying of the sapwood, the ability to identify those types of logs could not be investigated. However, the result appears promising because it was possible to correctly sort 70% of the logs in either a high- or low-mc group. With the described method, some assumptions about the relationship between the green heartwood density and the dry sapwood density must always be made. As described in the publication, there are sources of error in both the reference and predicted values. In the reference, the uncertainties are attributed to the mc of the conditioned disks, the volumetric swelling coefficient and the difference in the dry sapwood density between the butt ends of the logs and the density at a distance of 400 mm from the butt end. If the propagation of errors is calculated with one percent error in each one of these quantities according to equation (8), the typical error becomes approximately $\pm$5%.

$$\Delta u(\overline{x}, \rho_{0,green}) \approx \sqrt{\sum_{i=1}^{n} \left(\frac{\partial u}{\partial x_i}\right)^2 (\Delta x_i)^2 + \Delta \rho_{0,green}} \quad (8)$$

In the prediction, a small error is introduced when simulating the industrial X-ray log scanner and 3D data from the stem bank. However, the largest error occurs when trying to predict the dry sapwood density from the green heartwood density. By examining the variation in the average heartwood mc between different sites (published by Tamminen (1962)), an error of 5% is introduced to the prediction. By also examining the variation of the ratio between the heart- and sapwood density ($\rho_{0,green}$) between different individuals, another error with an approximate size of 10% is added, giving the predicted values a total uncertainty of approximately $\pm$15%.

Because the green heartwood mc is individual, and the relationship between the dry heart- and sapwood density also exhibits great variation between individuals, the described method can never be very accurate for single logs. However, it should be possible to find batches of logs from the same cutting site that started to dry in the forest before hauling to the sawmill. By working with larger batches, the possibility of adjusting the rest of the production chain in the sawmill to the incoming raw material can also be improved.

## Publication III

### *Material and Methods*

A common problem for many different measuring devices was addressed; namely, the difficulty of achieving accurate measurement results close to the board edges. A measuring device using microwaves at a frequency of 10 GHz was used. The transmitting antenna had two polarisation directions and a scattering dipole, was placed directly under the wood. This configuration produced a total of four combinations of phase shifts and attenuations that could be measured (Schajer and Orhan 2005). By using all four measured polarisation combinations, the attenuation and phase shift in the principal direction of the wood was calculated. Measurements were taken at different distances from the board edges, the behaviour of the system was compared to the behaviour of a FEM of the measurement system. To decrease the influence of the vicinity of the board edges, a correlation function for the behaviour of the simulation was introduced.

### *Results and discussion*

The measurements and the simulations of the measurement system showed that the distance from the edge of the board to the point at which the microwaves behaved as if the board was of infinite width was approximately 35 mm. By slightly changing the present setup of the system, it was concluded that the distance was not strictly 35 mm. Instead, it was affected by a sum of different parameters. Simulations of the system proved to be a valuable tool for further understanding and development of the system. By using a function to compensate for the distance from the measurement origin to the vicinity of the board edge, the non-useful range could be decreased from 35 to 19 mm. Despite the apparently small improvement, the useful measurement range of a 75 mm wide board is increased from 5 to 37 mm.

## Publication IV

### *Material and Methods*

At a modern sawmill, there are many different devices for measuring wood properties. The goal of publication IV was to investigate the possibility of increasing the accuracy of mc measurements by combining different measuring devices. A set of 195 Scots pine boards were planed to dimensions of 44 x 120 x 920 $mm^3$ and divided into five different groups, according to wood quality, by visual inspection. All of the boards were sawn with a 2ex sawing pattern. Of each group, half of the boards were conditioned to an mc of approximately 13%, and half were conditioned to approximately 16%. The different groups were defined by their characteristics. The "Defect" group contained large wood defects, such as top ruptures and spike knots, the "Knot" group contained considerably large sound knots, and the "Check" group contained checks of a size that was easily discovered with the naked eye. The wood classified as "Fine" had very few and small knots. Most of the "Fine" boards also contained a large amount of heartwood and had an average dry density higher than the other groups. Finally, the "Normal" wood group was chosen to represent the most common wood at a normal production site (i.e., neither of very high or low quality). From the perspective of an end user, the "Fine" group would be suitable for window frames, "Defect" would be suitable for packaging, and the other three groups would normally be used for construction. The typical magnitudes of some characteristic properties of the different wood groups were measured, and they are presented in Table 1.

*Table 1. Typical magnitudes of some characteristics of the wood in the different groups. The abbreviations are defined as follows: Cl=Check length, Cw=Check width, Kw=Knot whirls, Kd =Knot diameter, Fd=Fibre disturbance, $\rho_{0,u}$=density of dry wood at moisture content u.*

| Group | Cl (mm) | Cw (mm) | # Kw | Max Kd (mm) | Fd (mm) | $\rho_{0,u}$ (kg/$m^3$) |
|---|---|---|---|---|---|---|
| Normal | 0 | 0 | 1.7 | 23 | 0 | 400 |
| Fine | 0 | 0 | 1.3 | 7.5 | 0 | 450 |
| Knot | 0 | 0 | 2.2 | 34 | 0 | 400 |
| Check | 430 | 0.5 | 1.5 | 11 | 0 | 430 |
| Defect | 0 | 0 | 1.5 | 21 | 160 | 400 |

To get an idea of the visual appearance of the boards characteristics, three representative boards from each group are shown in Figure 6 to Figure 10. In the figures, only the parts of the boards from which data were collected (i.e., the centre 600 mm of the boards) are shown.

*Figure 6. Three characteristic boards from the group "Normal".*

*Figure 7. Three characteristic boards from the group "Fine".*

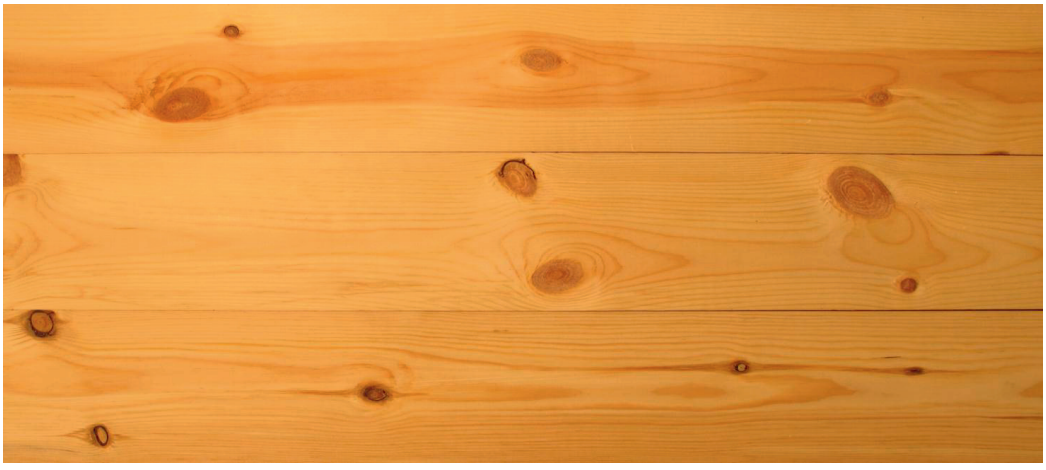

*Figure 8. Three characteristic boards from the group "Knot".*

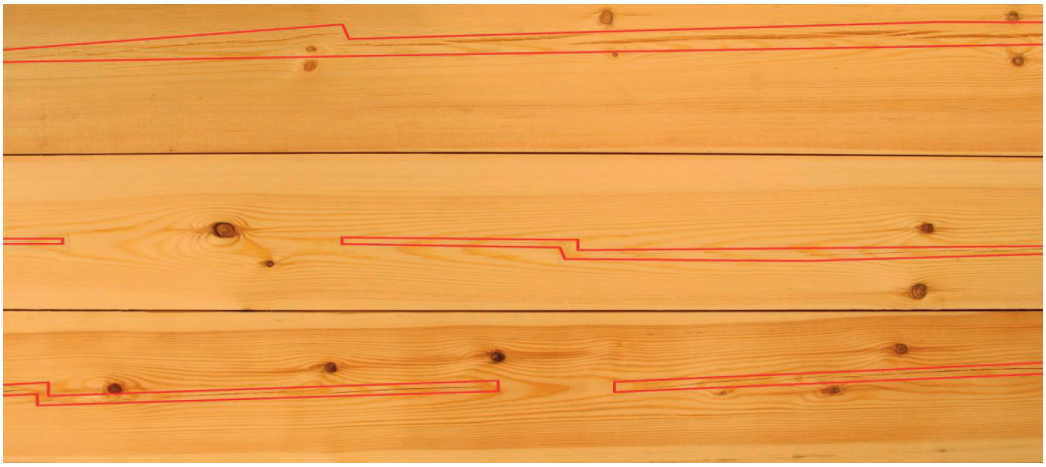

*Figure 9. Three characteristic boards from the group "Check". Because the checks are difficult to identify in the picture, they have been encircled with red lines.*

*Figure 10. Three characteristic boards from the group "Defect". Notice the grain deviation over large areas.*

As a calibration set, a total of 45 pieces that were conditioned to three different moisture content classes of approximately 8, 13 and 16% were used. The wood used for the calibration had the same characteristics as those of the "Normal" group, and they were not used in other measurements. The calibration set was kept relatively small to correspond to an industrial calibration procedure. The mc of each board was achieved by use of the oven-dry method. The attenuation and phase shift in two polarisation directions were measured with Satimo microwave equipment at a frequency of 9.375 GHz (Johansson 2001), as shown in Figure 11. When the boards where fed through the microwave equipment, their ends were supported by metal

racks, disturbing the EM field. In the analysis, only the mean values of the measured quantities from the centre 600 mm of each board were considered.

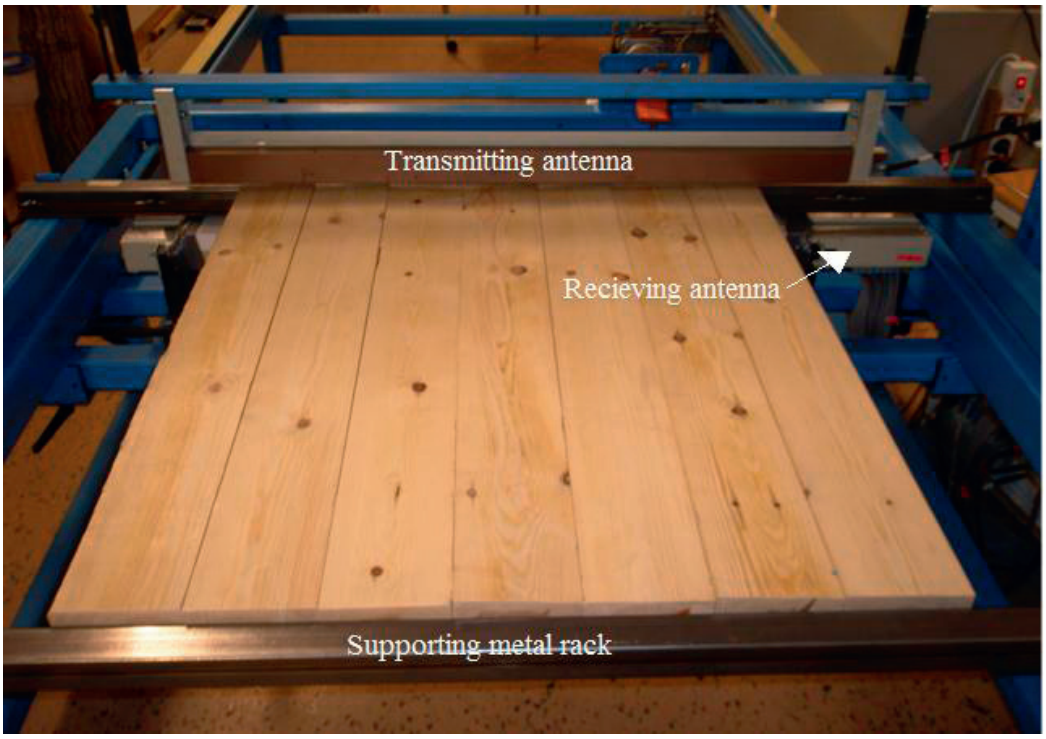


*Figure 11. Satimo microwave equipment. The two antennas and one of the supporting metal racks are marked in the figure.*

The wood density ($\rho_{u,u}$) was measured with a medical CT-scanner (Siemens Somatom Emotion Duo).

### *Results and discussion*

The average error, standard deviation, width of the 90% interval of confidence and percentage of pieces measured with a smaller error than 1% mc (including and excluding the average error) are shown in Table 2.

*Table 2. Mean errors ($\bar{\varepsilon}$), standard deviation (s), width of the 90% interval of confidence (c) and percentage of pieces for which the error in the measured mc was smaller than 1% mc. Number 1 refers to the model, in which only microwave measurements were considered, while 2 refers to the model in which microwave and computer tomography measurements were considered. The subscript with a single star refers to the percentage of pieces for which the deviation between the measured mc was within 1% mc of the oven-dry reference, while the subscript with two stars refers to the same quantity but with the average group error ($\bar{\varepsilon}$) subtracted from each single prediction. The unit of all numbers is percent (%).*

| Group | $\bar{\varepsilon}1$ | $\bar{\varepsilon}2$ | $s1$ | $s2$ | $c1_{90}$ | $c2_{90}$ | $1^{*}$ | $2^{*}$ | $1^{**}$ | $2^{**}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Normal | -0.65 | -0.55 | 0.85 | 0.65 | $\pm$0.23 | $\pm$0.17 | 65 | 83 | 73 | 90 |
| Fine | 0.18 | -0.21 | 0.63 | 0.59 | $\pm$0.17 | $\pm$0.16 | 85 | 93 | 90 | 93 |
| Knot | -0.36 | -0.37 | 1.0 | 0.89 | $\pm$0.28 | $\pm$0.24 | 70 | 73 | 86 | 86 |
| Check | 0.17 | -0.33 | 1.0 | 0.79 | $\pm$0.27 | $\pm$0.21 | 78 | 78 | 78 | 83 |
| Defect | -0.31 | -0.59 | 1.1 | 0.98 | $\pm$0.30 | $\pm$0.27 | 63 | 68 | 66 | 74 |
| All wood | -0.20 | -0.41 | 0.98 | 0.79 | $\pm$0.12 | $\pm$0.10 | 72 | 79 | 78 | 85 |

It is interesting to notice how the range of mean errors (in columns 2 and 3) decreases from 0.83% to 0.38% when the density measurements performed with the CT-scanner are added to the microwave measurements. The presence of an average error for the group “Normal”, which had the same characteristics as the calibration boards, indicates some discrepancy between the two groups. From the table, the increased difficulty of predicting the mc with good accuracy when more visual inhomogeneities are present in the wood can be seen. For application in the wood industry, the low accuracy of the mc measurements for the “Defect” group might not represent a significant problem because the boards of this group are of low grade anyway.

From the last column, one can see that the aim of the work is exactly fulfilled for the “Normal” group if the microwave and CT-measurements are combined with a visual sorting system. However, it should be kept in mind that this represents the “best possible scenario” in this work because the average group error is subtracted from each single measurement (as if the calibration was better than it actually turned out to be).

## Conclusion

Throughout this work, it was concluded that measurement of the mc is a difficult task. One of the associated problems is caused by the natural inhomogeneity of wood because knots, grain angles, compression wood, etc. all influence the measurements. Another problem is caused by the definition of mc itself because both the amount of water and the dry wood density must be measured. This requirement causes methods for which only one of the entities can be determined to fail as standalone solutions. One example of this difficulty is provided by the publication in which a prediction of the green sapwood mc was performed with a system that could only measure the total density. Despite the large errors in the method, it was possible to sort the majority of the logs into either a high or low mc group.

To understand the behaviour of a measuring system and its interaction with the wood, simulations have again proved to be a valuable tool. It was also shown that the combination of different measurement devices could be a relatively cheap way to improve the accuracy of the mc measurement. In publication IV, it was shown that the goal of measuring the mc of 90% of the boards within $\pm$1% mc was fulfilled for "normal" wood under ideal circumstances by combining measuring systems using microwaves, X-rays and visual sorting. However, this aim was not fulfilled with the original calibration.

## Future work

To gain the full benefit of the different measuring devices that are usually installed at large sawmills, it would be preferable to combine the measured quantities from different devices to increase the overall prediction accuracy of single quantities. To fully analyse the potential of combining methods, it would be of great interest to collect traceable data from the different devices in a sawmill over a longer period of time. Because of the great variation in wood parameters, good calibration of a measuring device is also difficult and time-consuming. When the dielectric properties of wood serve as the basis of the mc measurement, it is possible to save substantial time, effort and money by extensive investigation of the dielectric parameters of wood and the use of a calibration dummy with adjustable dielectric properties in the calibration procedure.

Another area of interest is the investigation of different measuring system configurations by simulation. In this work, it would be interesting to consider different measuring frequencies, antenna designs, shielding of the surroundings and the effects of different wood properties. The theoretical accuracy of different devices could also be investigated by using the apparatus signal-to-noise ratio of the measured phase shift and attenuation as the input data for simulations.

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# Appendix

## *Errata*

Publication I:

- On page 6 it is stated that; “En hyvlad yta ger en uppvisad fuktkvot som ligger en fuktkvotsprocent lägre..”. The correct text should be; “En hyvlad yta ger en uppvisad fuktkvot som ligger en fuktkvotsprocent högre..”.
- On page 14: The sentences “Potentialen hos metoden beräknades till 0.7 fuktkvotsprocent vid ett 95 % konfidensintervall. Vid de aktuella mätningarna uppnåddes dock bara en mätnoggrannhet om 1,1 fuktkvotsprocent med ett 90 % konfidensintervall” should be deleted.

# I

LULEÅ TEKNISKA UNIVERSITET

# Fuktkvotsmätare för träindustrin

## *En kartläggning av metoder för mätning av fuktkvoter i intervallet 7-18 fuktkvotsprocent*

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## 1 Introduktion

Trä som material har en konkurrensnackdel i att dess egenskaper varierar mycket, både mellan och inom en och samma individ. Att bättre än idag kunna sortera virke utifrån dess egenskaper skulle möjliggöra en ökad användning av trä som ett ingenjörsmässigt material och i förlängningen öka värdet på skogsråvaran. Inneboende faktorer som påverkar egenskaperna hos trä är bland annat kärnvedsandel, kvistandel, kvisttyp, fiberriktning, frodvuxenhet med mera. En av de viktigaste parametrarna att fastslå i träförädlingskedjan är fuktkvoten. Den behöver bestämmas för att kunna göra en korrekt hållfasthetssortering, säkerställa dimensionsstabilitet hos slutprodukten, förhindra mögeltillväxt etc.

Kunskapen om vad fuktkvoten hos virke är, på vilka sätt den påverkar produkten och att vatten finns dels bundet i virkets cellväggar och dels fritt i hålrum vid olika fuktkvoter är i många fall bristfällig. Detta kan ses bland många artiklar eftersom flertalet undersökningar att försöka bestämma fuktkvoten skett över stora fuktkvotsspann (ofta med fuktkvoter upp till åtminstone 70 %) och att definitionen som använts för fuktkvoten inte nämnts.

Målet med projektet i vilket följande studie gjorts är att hitta eller utveckla mätmetoder för fuktkvoter inom 7-18 fuktkvotsprocent på torr bas där 90 % av mätningarna ska ha ett mätfel understigande en fuktkvotsprocent oavsett mängden ved mätningen avser, eg. enbitsmätning eller batchmätning. Denna rapport innehåller korta beskrivningar av olika mätmetoder och deras noggrannhet.

### 1.1 Allmänt om fuktkvotsmätning på trä

Fuktkvoten hos trä brukar mätas som kvoten mellan massan vatten i en viss volym och den torra vedsubstansens massa inom samma volym. Formeln för fuktkvoten, u, blir då:

$$u = \frac{m_u - m_0}{m_0} = \frac{m_v}{m_0} \qquad (1)$$

där:

$u$ = fuktkvot

$m_u$ = massan hos fuktigt trä [kg]

$m_0$ = massan hos torrt trä [kg]

$m_v$ = massan hos vattnet i träet [kg].

Splintveden hos furu (*pinus sylvestris*) och gran (*picea abies*) har en fuktkvot i storleksordningen ~120-150 % i rått tillstånd medan kärnveden på desamma är i storleksordningen 30-40 % (Morén 2007).

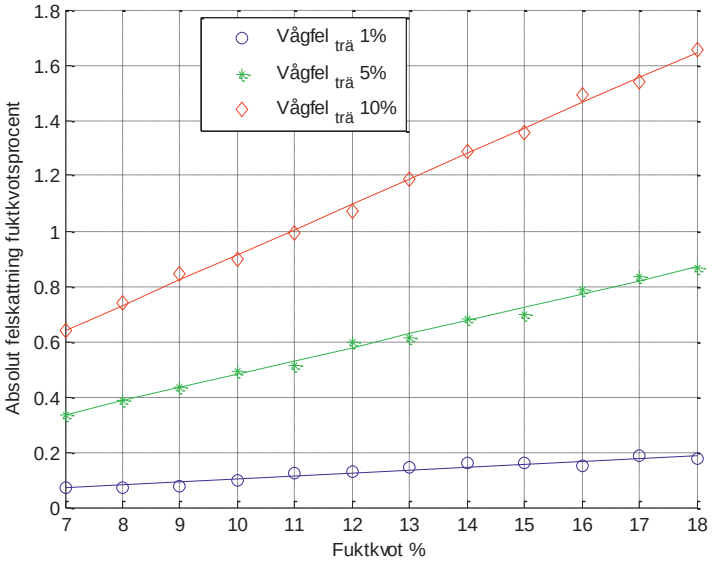
### 1.2 Känslighetsanalys

En kort översikt över mätfelens påverkan på fuktkvotsbestämningen i en torksats redovisas. Fel som diskuteras är felaktig bestämning av massan och volymen virke. Resultatet visar på att effekten av en enskild felkälla kan skattas med felets storlek i procent av den verkliga fuktkvoten. En storlek av felkällan på 5 % ger således vid 8 % fuktkvot ett fel på 0,4 fuktkvotsprocent medan motsvarande fel vid 16 % fuktkvot blir 0,8 fuktkvotsprocent. Känslighetsanalysen är giltig för alla mätmetoder men koncentrerar sig kring batchmätning i virkestork.

#### 1.2.1 Vägning

Noggrannheten hos metoder som bygger på att mäta eller uppskatta vikt eller densiteten hos virke kommer att påverka den skattade massan hos veden. Felen hos lastceller ligger i storleksordningen ±0,1 % medan felen hos truckvågar ligger inom ±0,5 % av vågens kapacitet vilket ger ett fel på en 20-tons truck inom ±100 kg. En noggrant bestämd vattenmassa i ett virkespaket ger att felet hos vågen ger ett fel i den skattade vedmassan. På ett 4m$^3$ virkespaket av gran motsvarar en felvägning på 100 kg ett densitetsfel på cirka 6,5 % (räknat på $\rho_{0/rå}$ om 385kg/m$^3$). Ur praktisk synvinkel kan

man använda kurvorna i Figur 1 även vid felskattning av vattenmassan (procentuellt). Samtliga beräkningar, där ej annat anges, har gjorts på furu med en densitet, $\rho_{0/rå}$, av 430 kg/m$^3$.



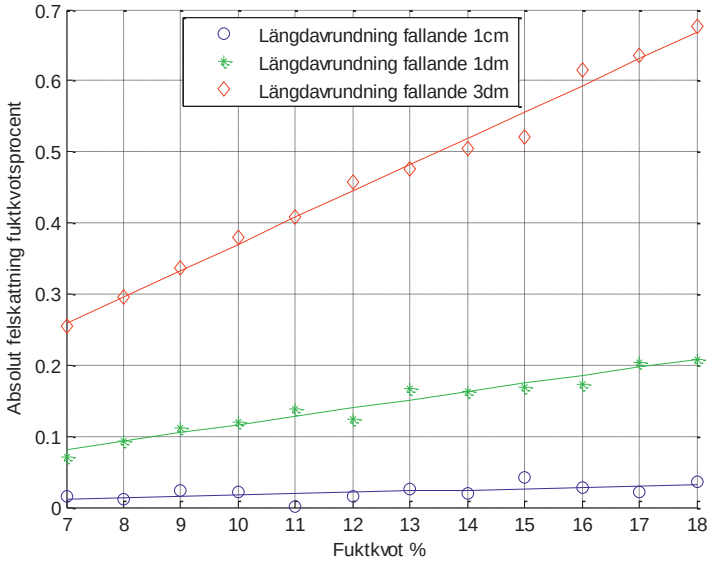

**Figur 1. Påverkan av felaktigt skattad virkesdensitet på skattad fuktkvot hos en virkesbatch.**

Ur Figur 1 kan man se att en felskattning av virkesmassan om 10 % redan vid 11 procents fuktkvot ger en felaktig skattning av fuktkvoten på en procentenhet. Eftersom standardavvikelsen på veddensiteten ligger runt 10 procent är det därför viktigt att nyttja en metod som istället mäter den verkliga densiteten på mindre partier virke. Punkternas avvikelse från den räta linjen i Figur 1 - Figur 4 beror på att en fördelning av virke med viss spridning simulerats.

### 1.2.2 Volymskattning

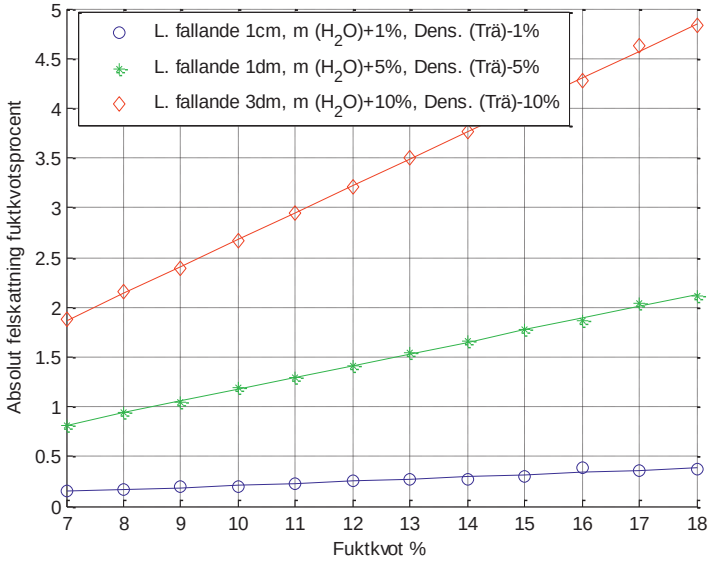
Den ingående volymen i ett virkespaket kan till exempel felskattas genom felaktiga råmått på virket eller ej noggranna längdmätningar på virket. Ifall längden mäts i fallande 3 dm moduler kan felen teoretiskt uppgå till 7,5 volymprocent för 4 meters virke under förutsättning att allt virke har en längd som ligger just under modulgränsen. I Figur 2 redovisas felen i fuktkvotsskattningen när virkeslängden avrundats till modulbotten. Virkets längd har antagits vara jämt fördelat i längder mellan 35 och 54 dm. En längdavrundning till fallande 3 dm moduler innebär därför att medelplankan har avrundats 15 cm. Längdfördelningen av virket ger en medellängd av 445 cm och således en underskattning av volymen om 3,4 %. Felaktiga råmått bör ge ett mindre volymfel än längdmätning med 3dm moduler. Till exempel ger ett 0,5 mm fel i råmåttet ett volymfel på 2,5 % för en 20 mm tjock bräda. Ett billigt sätt att minska felskattningen av volymen in i torken är att utföra längdmätning med åtminstone centimeter-precision ifall detta inte redan görs idag.

En simulering hur avrundningar i längdmåtten av virket på verkar fuktkvotsskattningen gjordes där virkeslängden avrundades till fallande 1cm, 1dm samt 3dm moduler respektive.




**Figur 2. Längdavrundnings, (i.e. volymfel), påverkan på den skattade fuktkvoten hos en virkesbatch.**

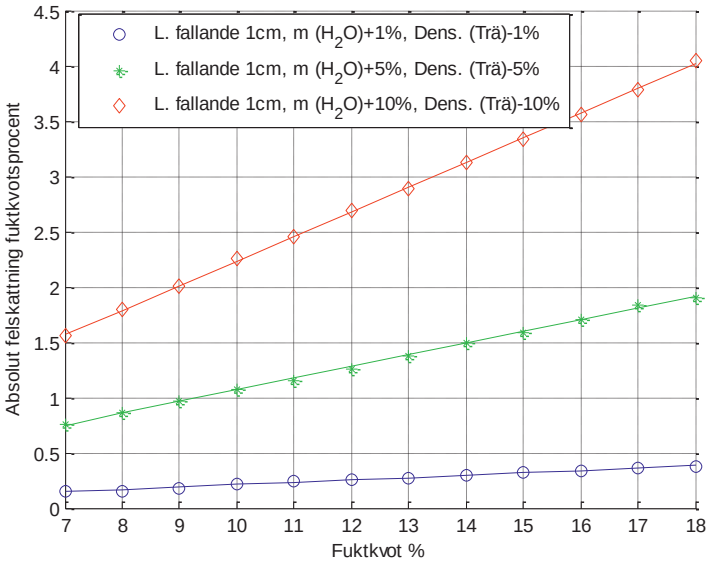
Vid bestämning av fuktkvoten behöver man titta på felkällornas sammanlagda inverkan. I Figur 3 redovisas en simulering där fel finns i vedvolymen, vattenmassan och trädensiteten. Felen har valts så att de samverkar och ger så stort totalfel som möjligt.




**Figur 3. Kombination av mätfel för volym, vattenmassa och trädensitet.**

Ur figuren ovan kan man se att totala felet när flera felkällor samverkar blir stort. För att få en noggrann bestämning av fuktkvoten är det därför viktigt att försöka bestämma samtliga ingående

faktorer med så stor noggrannhet som möjligt. Eftersom längdmätning inom centimeter-precision är enkel att åstadkomma upprepades simulering enligt Figur 3 men med längdavrundning till fallande 1cm klasser i samtliga fall. Resultatet redovisas i Figur 4.




**Figur 4. Kombination av olika mätfel med en noggrann volymskattning.**

Genom att jämföra Figur 3 och Figur 4 kan man se att en stor förbättring av mätnoggrannheten kan åstadkommas endast genom att förbättra volymskattningen.

## 2 Mätmetoder

### 2.1 Resistiva mätare

Resistiva fuktkvotsmätare utnyttjar förhållandet mellan resistansen i veden, eller impedans i fall där mätaren använder växelspänning, och dess vatteninnehåll. Vid fuktkvoter under fibermättnadsfuktkvoten är motståndet kraftigt beroende av vedens fuktinnehåll medan beroendet avtar då fuktkvoten överstiger fibermättnadsfuktkvoten. Vid de höga fuktkvoterna är det istället andra ämnen i veden som främst påverkar motståndet som till exempel saltinnehållet (Esping 1992).

Tidigare undersökningar av handhållna resistiva fuktkvotsmätare (Forsén and Tarvainen 2000) fastslår vikten av en noga kalibrerad mätare. Stora skillnader i kalibreringskurvorna påvisas för virkestemperatur, kärnved/splintved och elektrodernas utformning. Ingen signifikant skillnad beroende på mätriktning i förhållande till fiberriktning, vedens densitet eller elektrodavståndet påvisas.

Industriella försök att bestämma slutfuktkvoten hos en virkesbatch under torkning, (Fløtaker and Tronstad 2000), visar att medelfuktkvoten bör mätas före en eventuell konditioneringsfas. Medelfuktkvoten kunde, för alla fyra testomgångar, bestämmas inom 1,4 fuktkvotsprocent med ett 90 % konfidensintervall, detta efter att en ny resistanskurva utarbetats. Resultatet ska därför ses som ett mått på metodens potential.


**Figur 5. Exempel på handhållen resistiv fuktkvotsmätare(1).**

## 2.2 Kapacitiv mätare

Kapacitiva mätare är idag den vanliga typen av inlinemätare i sågverksindustrin. Mätvärdet för kapacitansen hos träet beror på den dielektriska konstanten (Skaar 1988). Den dielektriska konstanten är ett mått på polariseringen hos atomerna och molekylerna i ett material när detta placeras i ett elektriskt fält. Enligt (Torgovnikov 1993; Forsén and Tarvainen 2000) kan åtminstone fyra olika typer av polarisering ske i trä beroende på vilken mätfrekvens som används. Dessa fyra är elektron-, atom-, dipol- och interfacial polarisering. De två första är av primärt intresse vid användandet av optisk och infraröd spektroskopi medan de två senare är vad som främst mäts när man använder elektriska metoder med frekvenser av storleksordningen mikrovågor och lägre.

Vid en undersökning som utfördes av Trätek visade den bästa av de fyra undersökta inline-mätarna, Brookhuis, Exotek, Quasar och Wagner, en mätnoggrannhet på individnivå med 90 % av individerna inom 2,4 fuktkvotsprocent och en repeterbarhet inom 1,8 fuktkvotsprocent (Esping 2003). En äldre undersökning av inline-mätare fastslår att densitetskompensation sänker medelkvadratfelet från 2,9 till 2,1 (Eliasson 1989).

Undersökning av en handhållen kapacitiv fuktkvotsmätare (Garrahan and Lavoie 2005) visar följande:

- En hyvlad yta ger en uppvisad fuktkvot som ligger en fuktkvotsprocent lägre jämfört med motsvarande virke med sågad yta.
- Virkets temperatur påverkar mätningen med 0,0477 fuktkvotsprocent per grad Celsius.
- Virkets dimension påverkar den uppmätta fuktkvoten.
- Tjurved och kvist påverkar inte den uppmätta fuktkvoten ifall hänsyn tas till den faktiska densiteten.
- Ingen skillnad mellan mätresultat kunde påvisas mellan virke torkat vid två olika torktemperaturer, 82 respektive 110 $C^{O}_{torr}$.

Enligt uppgifter från en säljare av kapacitiva inline-fuktkvotsmätare finns den största förbättringspotentialen i att använda sig av densitetskompensering, kompensering för plankans position relativt sensorn samt temperaturkompensering (Rasimus 2010).

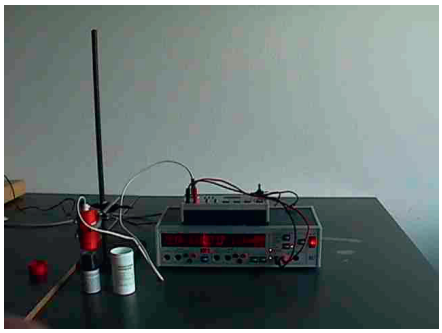
Ifall mätaren endast består av ett mäthuvud, som oftast är fallet med handhållna mätare, påverkas mätresultatet i stor utsträckning av fuktkvoten i ytan där fältet är starkast. Två mäthuvuden som kan mäta den dielektriska konstanten både mellan mäthuvudena och runt respektive mäthuvud ger därför en möjlighet, åtminstone i teorin, att mäta fuktkvotsgradienten.

En mätuppställning som kombinerar den kapacitiva och resistiva mätningen är den elektriska impedansspektroskopin vilken genom att använda olika frekvenser och därigenom erhålla olika inträngningsdjup kan skatta både medelfuktkvoten och fuktkvotsgradienten. En portabel utrustning som utvecklats i Finland (Tiitta and Olkkonen 2002) gav sämre skattning av medelfuktkvoten än kommersiella kapacitiva givare men en ökad möjlighet att upptäcka fuktkvotsgradienter.

**Figur 6. En modell av kapacitiv inlinefuktkvotstmätare (2).**

## 2.3 Gammastrålning

Gammastrålar är de elektromagnetiska vågorna med högst energi och frekvens. Ifall man ska prata om våglängder, vilket kan vara förvirrande eftersom dessa är så korta att man lämpligast istället bör prata om energier, är dessa i storleksordningen mindre än en picometer. Genom att mäta dämpningen av gammastrålar när dessa passerar ett medium kan du få en uppfattning om materialets täthet. Med bara en mätning kan dock inte veden och vattnet särskiljas (Tiitta, Olkkonen et al. 1993).



**Figur 7. Laborationsuppställning av mätsystem för gammastrålning (3).**

## 2.4 Röntgen

Röntgenstrålning har relativt kort våglängd, (0,06-125nm), och hög energi. Detta gör att den får en hög inträngningsförmåga i olika material. Metoder med flera olika energinivåer kan öka informationen från mätningen eftersom molekylerna reagerar olika vid olika våglängder. Genom att använda minst två distinkta energinivåer kan därför en viss särskiljning av vatten respektive vedmängd göras. Ett försök att bestämma fuktkvoten hos granflis, (rå bas), genom att använda två energinivåer (Hultnäs, Kullenberg et al.) gav en standaravvikelse runt 0,5 fuktkvotsprocent i en repeterbarhetstest av tio mätningar per varje objekt. Vid undersökningen användes även väldefinierade prover samt mättider på runt en minut för att förbättra signal-brus förhållandet.

Mätningar av bland annat fuktkvoten hos virke har utförts i forskningssyfte under pågående torkning och man har då visat på en maximal teoretisk standardavvikelse på 0,6 fuktkvotsprocent för virke under fibermättnadspunkten (Baettig 2006). Det ska noteras att vid försöket torkades och undersöktes endast en planka per gång i en liten labb-tork vilket underlättar mätningen avsevärt.

En röntgendetektor kan byggas som en lång endimensionell detektor och man kan därför få till stånd ett stort mätområde för varje strålkälla vid en tvärmatning. Kombinerad med en metod som med stor noggrannhet mäter antingen veddensiteten eller vattenmängden är det därför troligt att en god fuktkvotsmätning skulle erhållas.

**Figur 8. Tomograf för forskningsändamål (4).**

## 2.5 NIR

NIR (Near Infra Red) ligger i det elektromagnetiska spektrumet nära synligt ljus med våglängder på 780-3000nm (Hecht 2002). Vid undersökningar med hjälp av NIR erhålls ett spektra med vibrationsenergierna hos det undersökta materialet. Alla molekyler har sina speciella energinivåer för vibrationerna. Spektrumet som i slutändan ska analyseras innehåller många överlappningar och kombinationer av vibrationer vilket gör det svåranalyserat. Med NIR kan mycket information tolkas ur en enda mätning vilket kan ses som en fördel samtidigt som det förutsätter att man har bra koll på en rad ingående parametrar för att undvika feltolkning. Några parametrar som påverkar spektrumet är: vatteninnehåll (kan delas in efter hur detta är bundet), temperatur, fibervinkel, ytans beskaffenhet, extraktivämnen, mikrofibrillvinkel mm. (Tsuchikawa 2007). Med hjälp av NIR är det möjligt att direkt mäta fuktkvoten i trä. NIR har, på grund av sin våglängd, ett dåligt inträngningsdjup vilket gör att mätningen endast sker i ytskiktet. Medelfuktkvoten hos en planka kan därför inte mätas med bara NIR, däremot kan metoden tillsammans med en annan mätmetod ge en uppskattning av fuktkvotsgradienten.

**Figur 9. Exempel på utrustning för NIR-analyser (5)**

## 2.6 Mikrovågor

Mikrovågor är i det elektromagnetiska spektrumet placerat mellan radiovågor och infraröda vågor, det vill säga våglängder mellan 1mm till 30 cm. Den relativt långa våglängden, d.v.s. ett långsamt varierande elektromagnetiskt fält möjliggör för dipolära molekyler, till exempel vattenmolekyler, att ställa sig parallellt med fältet när detta byter riktning. Molekylerna behöver energi för att ställa sig parallellt med det pålagda elektromagnetiska fältet, energi som tas ifrån detta. Mängden vattenmolekyler i ett material kan därför mätas genom att mäta energiförlusten av ett elektromagnetiskt fält, med våglängder i mikrovågsområdet, när detta passerar genom ett material.

Eftersom elektromagnetiska vågor färdas långsammare i ett material än i vakuum uppstår alltid en förskjutning av fasen när en våg passerar genom ett material vilket kan förstås som att vågen behöver längre tid på sig när denna ska passera genom ett material jämfört med vakuum. Förenklat sett beror energiförlusten på vattenmängden, fasskiftet på en kombination av fukt och veddensitet och förändringen av polariseringen på fiberriktningen (James, Yen et al. 1985). Mikrovågorna påverkas även olika beroende på våglängd, fiberriktning, temperatur, veddensitet, dimension och på vilket sätt vattenmolekylen är bunden till materialet (Okamura 2000). I artikeln listas även fem olika mätuppställningar för fuktkvotsmätningar, dessa är: ”fri-rymdsmetoden” (strålkälla och mottagare på olika sidor om mätobjektet), transmissionsmetoden, reflektionsmetoden, resonansmetoden och TDR (se separat kapitel).

Mikrovågor kommer alltid, eftersom de sätter vattenmolekylerna i rörelse, att avge energi till mätobjektet. För att mäta fuktinnehållet räcker det dock med små energinivåer och därför blir värmningseffekten försumbar. Vid låga fuktkvoter kommer alltid signal-brus förhållandet att vara lägre eftersom dämpningen är mindre vilket innebär att mätresultaten vid låga fuktkvoter inte är lika pålitliga. Frusen ved kommer även att indikera för låg fuktkvot eftersom vattenmolekylerna inte har samma möjlighet att vrida sig med fältets riktning (Hansson, Lundgren et al. 2005).

I en undersökning där en slitsad vågledare användes som ett strö kunde medelfuktkvoten under torkning beräknas inom två fuktkvotsprocent med ett 90 % konfidensintervall vid fuktkvoter under 15 % (Holmes and Riley). Metoden verkar lovande men har följande nackdelar: extraarbete för sågverkspersonalen, känslig utrustning måste placeras i virkestorken, mätaren behöver strömförsörjning vilket gör den svår att använda i en vandringstork.

**Figur 10. Inlinefuktkvotsmätare som använder mikrovågor (6).**

## 2.7 Radiovågor

Radiovågor är de vågor med den längsta våglängden i det elektromagnetiska spektrumet (från 30cm till flera kilometer). Det finns idag kommersiella fuktkvotsmätare som använder sig av radiovågor för att mäta fuktkvoten på enbitsnivå, se Figur 11. Radiovågor har även använts för att försöka bestämma medelfuktkvoten av en virkeslast under pågående torkning. Inga publicerade resultat på detta har dock hittats. Vid fuktkvotsbestämning av värmeflis har provmaterialets temperatur visats vara försumbar inom intervallet 2-60˚C (Paz, Nyström et al. 2006). En utvärdering av radiovågor för att bestämma vattenhalten i värmeflis gav ett medelkvadratfel på modellen av 4.9 vattenhaltsprocent (Paz, Nystöm et al. 2008). Vid den aktuella undersökningen innehöll flisen ungefär 25-65 vattenhaltsprocent.


**Figur 11. Exempel på en fuktkvotsmätare som använder sig av radiovågor (7).**

## 2.8 NMR

NMR, Nuclear Magnetic Resonance, använder spinnet hos atomer, i fallet där vattenmängden ska mätas protonen $H^+$, för att skapa en mätbar signal. Kärnspinnet kan sägas ha en viss riktning och kan lämpligt liknas vid en vektor. Utsätter man mätkroppen för ett externt magnetfällt kommer dessa vektorer att orientera sig parallellt med det externa fältet. Ifall man sedan utsätter mätkroppen för en elektromagnetisk våg kommer denna att få alla spin att oscillera, oscillationer som går att mäta genom den spänning de inducerar i en spole. Hur snabbt den inducerade signalen avtar är olika för olika material och genom att mäta detta kan man till exempel bestämma hur mycket vatten som finns i veden. Metoden fungerar ännu bättre ifall hänsyn tas till vedens kemiska sammansättning. Ett kalibrerat system, där provbitarna även vägs ger resultat på fuktkvoten som är jämförbart med torrviktsmetoden (Merela 2009)

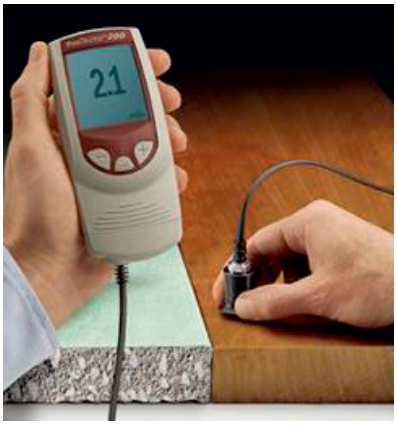
Enkelt uttryckt kan man mäta mängden molekyler/atomer av olika slag i mätobjektet. Metoden kan även utnyttjas med hjälp av mindre permanentmagneter med den nackdelen att signalens härkomst endast går att bestämma i en dimension, det vill säga avståndet från mätaren. Fördelarna ligger i priset för både inköp och användande av utrustningen.

En undersökning av en handhållen NMR-sensor visar på ett tydligt samband mellan fuktkvoten och den mätta signalen (Prado 2001). Undersökningen utfördes som ett led i att bestämma potentialen hos metoden för att bestämma fuktkvoten. Nämnas ska att undersökta fuktkvotsintervallet låg ungefär mellan 20 och 75 % fuktkvot och bestod av endast 9 mätpunkter. I en annan undersökning som gjorts kunde en regressionsanpassning för mätning av fuktkvoten hos ”Western red cedar”, där denna jämfördes med torrviktsmetoden, erhållas med ett $R^2$-värde på 0,9916 (Bucur 2003).

**Figur 12. Exempel på en handhållen NMR-magnet (8).**

## 2.9 Ultraljud

Ultraljud bygger på att en ljudvåg går in i materialet som ska mätas. Mätning kan ske antingen på den transmitterade eller reflekterade vågen som är fallet vid vanliga mammografiundersökningar. En metod där den reflekterade vågen mäts skulle ge möjlighet att mäta en fuktprofil under förutsättning att vågen reflekteras på olika djup. Vid en mammografiundersökning ses egentligen övergångarna mellan olika medium t.ex. muskel, ben, vatten medan ett virkesstycke saknar dessa tydliga skillnader annat än på mikroskopisk nivå. Ett försök att kalibrera en beröringsfri ultraljudsutrustning för att mäta fuktkvot på ”red pine” (*Pinus resinosa*) visar på att det finns ett samband mellan fuktkvoten och ljudhastigheten respektive transmittansen (Vun, Hoover et al. 2008). Resultaten påvisar dock stort brus i mätningarna och att använda metoden för att bestämma fuktkvoten skulle ge stora felaktigheter i fuktkvotsskattningen.




**Figur 13. Figuren visar en variant av en ultraljudsmätare (9).**

## 2.10 Gravimetriska metoder

Metoden är att bestämma massan på veden vid den aktuella fuktkvoten. För att bestämma fuktkvoten i virket behöver antingen vedens torra massa eller vattnets massa vid en viss mätning vara känd.

Metoden skulle fungera i en virkestork om man vid någon speciell tidpunkt kunde få en signal på vattnets massa och sedan använda denna punkt som referens och mäta massförändringar när torkningen fortskrider. Försök har gjorts där massan hos enskilda virkesstycken såväl som hela virkesstaplar bestämts under pågående torkning. Mätningen blir bättre på en hel virkesstapel än på enbitsnivå eftersom medeldensiteten på en virkesstapel varierar mindre än densiteten hos en enskild individ. Industriella försök, utförda av NTI, där en virkesstapel vägdes under pågående torkning visar på vikten av en noggrant bestämd virkesdensitet. När tabellvärden användes blev feluppskattningarna av fuktkvoten upp till 15,1 % -enheter. När istället den uppmätta medeldensiteten för furu (*Pinus sylvestris*) respektive gran (*Picea abies*) användes blev feluppskattningarna mellan 2,2 och 8,2 fuktkvotsprocent (Fløtaker and Tronstad 2000).

Torrviktsmetoden som används för att mäta fuktkvoten enligt standarden, ISO 4470, är en variant av en gravimetrisk metod där massan hos en provbit bestäms innan denna torkas vidare i ugn tills förändringen av massan hos provbiten inte är större än 0,1 % per timme. Genom att mäta massan hos det torra provet kan sedan fuktkvoten vid den första mätningen bestämmas genom att använda ekvation 1. Eftersom metoden är tidsödande och förstörande är den endast aktuell för noggrann mätning av fuktkvoten hos ett begränsat antal individer i produktionen. En gemensam felkälla som finns hos alla metoder där totala massan ska bestämmas genom vägning är vågens precision. Det är därför viktigt att använda en kalibrerad våg med tillräckligt hög upplösning för ändamålet. Speciellt för torrviktsmetoden finns en rad andra felkällor som uttorkning vid provtagning eller mellan provtagning och första vägning, dålig ventilerad ugn, felaktig värme i ugnen, uttorkning av lättflyktiga ämnen som tolkas som vatten, vattenabsorption efter torkning samt att spån och små träflisor faller av provbiten under torkningen (Esping 1992).

Att använda lastceller i virkestorken och mäta en hel virkesstapels massa kan vara ett någorlunda robust system. Möjligheten att spåra individer genom systemet tillsammans med en fuktkvotsmätare för rått respektive torkat virke skulle ge en värdefull databas med bra möjligheter för att ytterligare utveckla torksimuleringarna. Lastceller skulle i så fall kunna monteras i de virkestorkar där speciellt värdefulla produkter torkas för att på så sätt få en indikation om slutfuktkvoten samtidigt som databasen, som går att använda i samtliga torkar, fylls på.


**Figur 14. Exempel på en lastcell av ”S-typ” (10).**

## 2.11 Krympningsmätning

Virke sägs vid fibermättnadsfuktkvoten, som ligger runt 28-30 % fuktkvot (Esping 1992), vara tömt på fritt vatten i lumen och endast innehålla vatten i cellväggarna. Vid ytterligare torkning, det vill säga när vatten försvinner ur cellväggarna krymper dessa. Genom att mäta krympningen av en planka kan man därigenom uppskatta fuktkvoten under fibermättnadsfuktkvoten. Variationen i krympning mellan individer är, även när dessa är sågade till samma dimension och härrör från samma position i stocken, stor (Hájek and Esping 1996). Skattning av fuktkvoten hos en enskild individ genom att mäta krympning ger därför ett osäkert resultat. Metoden är därför främst lämplig för att mäta medelfuktkvoten i en torksats genom att utföra krympningsmätningen på ett stort antal individer.

Tidigare undersökningar där den totala höjden på en virkesstapel uppmätts visar på problem med strölagrens krympning, virkets kupning och skevning samt intryckningen av stön i virket på grund av den höga belastningen (Fløtaker and Tronstad 2000). I samma undersökning påtalas fördelarna med att endast mäta virkets krympning. Denna mätning bör i så fall, av praktiska skäl, ske optiskt och beröringsfritt på en kantsida av en virkesstapel. Skillnaden är då att mätningen inte görs på ren radiell krympning utan snarare på en kombination av radiell och tangentiell krympning samt att en fri kant under torkning kommer att torka något snabbare än medelplankan i hela torksatsen och därför indikera en för låg medelfuktkvot. Märgplaceringen i plankorna, att dessa har skarpa sidor som är enkla att mäta samt kantplankornas representativitet för medelplankan (vilket är av speciellt intresse när plankor från flera positioner i en stock torkas tillsammans) behöver därför hållas i åtanke.

Miljön i en virkestork med hög värme och fuktighet samt lättflyktiga ämnen i torkluften som avgetts från virket och cirkulerar med torkluften ger ett ogynnsamt klimat för all utrustning. Ifall en kamera placeras inuti virkestorken för att fotografera kantsidan på en virkesstapel behöver linsen hållas fri från fukt och smuts. Klimatet kan dessutom direkt påverka uppmätta resultat ifall mätutrustningen har ett temperaturberoende eller fuktkvotsberoende.

**Figur 15. Strölagt virkespaket.**

## 2.12 Neutronkällor

Möjligheten finns att mäta vatteninnehållet i ett ämne med hjälp av att beskjuta detta med neutroner och jämföra antalet neutroner som tar sig igenom materialet med antalet som tar sig till detektorn när ingen provbit ligger i mätområdet. Experimentella data som jämförts med teoretiska värden genom Monte-Carlo simulering visar på svårigheter att exakt bestämma fuktkvoten trots att varje prov hade en mättid om 5-10 minuter (Naqvi 2003). Neutronkällor har även använts för att skatta fuktkvoten av en virkesbatch under pågående torkning (Fløtaker and Tronstad 2000). En neutronkälla och en sensor som monterats bredvid varandra placerades under en virkesstapel. Sensorn mätte på så sätt indirekt diametern på mätloben eftersom denna ökar när vätekoncentrationen sjunker, det vill säga när vatteninnehållet i virket minskar. Potentialen hos metoden beräknades till 0.7 fuktkvotsprocent vid ett 95 % konfidensintervall. Vid de aktuella mätningarna uppnåddes dock bara en mätnoggrannhet om 1,1 fuktkvotsprocent med ett 90 % konfidensintervall. Den aktuella mätuppställningen skulle även fungera bra i en vandringstork eftersom hela mätutrustningen var infälld i golvet och mätte fuktkvoten beröringsfritt. Viktigt att notera är att i rapporten understryks flera gånger att placeringen av paketet och individerna påverkar mätresultatet. Mätmetoden kan inte heller särskilja vatten eller vedmängd vilket gör att det krävs en känd kalibreringspunkt.

**Figur 16. Exempel på utrustning för att mäta dämpningen av neutroner (11).**

## 2.13 TDR-Time Domain Reflectometry

Arbetsprincipen för TDR är liknande den för ultraljud. Genom att skicka in en elektromagnetisk våg i ett material och mäta reflekterad amplitud som funktion av tiden kan en skattning göras av fuktinnehållet i ett material (Cerný 2009). Metoden bygger på att stift slås in i materialet och vågen skickas mellan dessa (Okamura 2000). Mätningar av hur fuktkvoten i levande träd förändras under åren har gjorts, det vill säga mätningar på fuktkvoter över fibermättnadsfuktkvoten och utan säkra referenser (Wullschleger, Hanson et al. 1996).

**Figur 17. TDR-utrustning (12).**

## 2.14 Multisensorsystem

Ett problem som återkommer för alla mätmetoder i större eller mindre utsträckning är att fuktkvotsmätningar förutsätter att både massan vatten och massan ved i en viss volym är känd. Medan vissa metoder är bra på att mäta totala massan, till exempel metoder som använder sig av röntgen eller gammastrålar; andra metoder snarare vatteninnehållet, t.ex. kapacitiva mätare. Fåtalet mätare kan, åtminstone delvis, särskilja vatten och vedmängd, till exempel NMR, neutronkällor. För att få till stånd en noggrann fuktkvotsmätning är det därför troligt att flera olika mätmetoder bör kombineras. Kombinationen av mätmetoder skulle även öka precisionen då kalibreringen kan ske för kombinationen av flera mätares resultat på samma individ istället för på en enskild mätare åt gången.

## 3 Sammanfattning

Mätning av fuktkvot i virke är en svår uppgift vilket kan förstås av hur mycket arbete som tidigare lagts ner för att hitta den perfekta mätmetoden. Det är knappast troligt att mycket bättre resultat än vad som erhålls idag kommer att kunna uppnås utan att kombinera flera olika mätprinciper. För att mäta medelfuktkvoten i en virkeslast under torkningen vore det även önskvärt att undvika placering av avancerad och dyr mätutrustning inne i det tuffa klimat som råder i en virkestork. Ett intressant alternativ vore billiga resistans och temperaturmätare som kunde placeras på virket redan i råsorteringen. Med grund i vad som hittats i artiklar och rapporter och som sammanställts i denna text presenteras en överskådlig sammanställning av mätmetodernas prestanda för enbits- respektive batchmätning i Tabell 1 och Tabell 2. Det är viktigt att notera att betygssättningen är godtycklig.

**Tabell 1. Mätmetoder, dess teknikmognad och potential för fuktkvotsmätning vid enbitsmätningar.**

| Metod | Teknikmognad | Potential (Fuktkvot) |
|---|---|---|
| Resistiva mätare | +++ | ++ |
| Kapacitiva mätare | +++ | ++ |
| Gammastrålning | + | ++ |
| Röntgen | + | ++ |
| NIR | + | + |
| Mikrovågor | ++ | +++ |
| Radiovågor | ++ | +++ |
| NMR | + | +++ |
| Ultraljud | + | + |
| Neutronkällor | 0 | ++ |
| TDR | + | + |
| | *+++ Vanliga i industrin* | *+++ Hög* |
| | *++ Finns i industrin* | *++ Medel* |
| | *+ Teknik välkänd* | *+ Låg* |
| | *0 Osäker* | *0 Osäker* |

**Tabell 2. Mätmetoder, dess teknikmognad och potential för fuktkvotsmätning vid batchmätningar.**

| Metod | "Teknikmognad" | Potential (Fuktkvot) | Användarvänlighet |
|---|---|---|---|
| Resistiva mätare | ++ | +++ | + |
| Kapacitiva mätare | + | ++ | ++ |
| Mikrovågor | 0 | ++ | ++ |
| Radiovågor | + | + | ++ |
| Neutronkällor | + | + | ++ |
| Vägning | ++ | + | +++ |
| Krympning | ++ | ++ | ++ |
| | *+++ Vanliga i industrin* | *+++ Hög* | *+++ Lite extraarbete* |
| | *++ Finns i industrin* | *++ Medel* | *++ Visst extraarbete* |
| | *+ Teknik välkänd* | *+ Låg* | *+ Mycket extraarbete* |
| | *0 Osäker* | *0 Osäker* | |

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# II

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**ORIGINAL ARTICLE**

# Sapwood moisture-content measurements in *Pinus sylvestris* sawlogs combining X-ray and three-dimensional scanning

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**Abstract**
Because today's sawmill processes are not fully adapted to the variability of the raw material, it is crucial to sort sawlogs according to material properties in order to process the wood efficiently and to obtain high-quality end-products. One material property that could be used for sorting is the moisture content (MC) of the sapwood, an important parameter for both the processing and the end-products. Most sawmills use three-dimensional (3D) scanners to sort logs and some have also invested in X-ray scanners. Previous studies have shown that, by combining raw data from 3D and X-ray log scanners, green sapwood density and dry heartwood density in Scots pine sawlogs can be estimated. In this study, the method was used to estimate sapwood MC in green logs. It was found that the MC estimate could be used to separate the logs into groups with high and low MC, correctly classifying all logs with MC below 100% as low MC logs. Out of all logs, 70% were correctly classified. The MC estimate could also be compared to the dry density-dependent maximum MC and used to identify logs that have actually started to dry.

**Keywords:** *3D scanning, green density, log sorting, MC, Scots pine, X-ray scanning.*

## Introduction

Wood is a biological material with great variations in material properties between individual logs and within the same log. The wood industry of today deals with large volumes in an almost automatic process, which is not fully adapted to the variability of the raw material. Thus, the sawn wood also shows a great variability in material properties, and a large share of the production carries combinations of dimension and grade that do not meet customer requirements (Grönlund, 1992). To reduce the production of off-grade products, the sawlogs may be sorted according to specific material properties or predicted grade of the sawn goods before sawing. This enables the sawmill to saw each log into dimensions where the grade of the log is best utilized, thus improving the value of the sawn wood.

Sorting of logs or sawn goods according to certain material properties also helps the sawmill to adjust the process so that the wood can be processed efficiently and the highest possible quality of the end-products can be obtained. Heartwood content, wood density and sapwood moisture content (MC) are examples of properties important to the drying process. Boards with similar density and moisture-content distribution show similar behaviour during drying, and by sorting the boards according to these parameters before drying, well-adapted drying schedules can be constructed with respect to time, energy consumption and quality of the final products. If the initial MC in the batch is known, over-drying can be reduced when using fixed schedules, and the finishing time can be predicted more accurately when using adaptive schedules (Larsson & Morén, 2003).

In the green sorting, heartwood content can be measured using, for example, laser systems (Oja *et al.*, 2006), and wood density and average MC can be measured using microwave scanning (Johansson *et al.*, 2003). Using these techniques, it is possible to sort the sawn goods with respect to drying

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properties. By this approach, however, the volumes sorted into each class is not known in advance, and consequently the production cannot be planned to achieve optimum filling in the kilns. To avoid this problem, it would be desirable to perform sorting based on drying properties earlier in the process at the log-sorting station.

In the log sorting, inner properties of logs such as heartwood content (Skatter, 1998; Oja *et al.*, 2001) and density (Oja *et al.*, 2001) can be measured using an X-ray log scanner. Most sawmills installing an X-ray log scanner already have an optical three-dimensional (3D) scanner present, and it has been shown that the combination of both scanners can be used to sort logs with improved precision (Skog & Oja, 2009). The combined 3D X-ray method has been used to measure heartwood diameter (Skog & Oja, 2009), green sapwood density and dry heartwood density in Scots pine sawlogs (Skog & Oja, 2010). However, so far no method for measuring MC in the log sorting has been presented. The hypothesis of this study is that it should be possible to use dry heartwood density to estimate the dry sapwood density, and that the dry and green sapwood densities can be combined to obtain the sapwood MC in the log. Sorting the logs based on this information would result in batches with more homogeneous material properties, which would be helpful when optimizing the processing of the logs.

The aim of this study was to develop a sapwood MC calculation model and to evaluate the feasibility of this method for the sorting of sawlogs.

## Materials and methods

### *Calculation of reference values*

The development of MC calculation algorithms requires a set of sawlogs with well-defined green and dry densities. In this study, the computed tomographic (CT) scanned logs of the Swedish pine stem bank (Grundberg *et al.*, 1995) were used. The stem bank contains a total of 560 Scots pine sawlogs (165 butt logs and 395 upper logs), for which cross-sectional CT images are available every 10 mm within knot whorls and every 40 mm between whorls, giving a good knowledge of the green density in the logs. For each log, a reference value for the green sapwood density, $\rho_{u,u}$, was calculated by taking the average over the sapwood of a knot-free cross-section approximately 400 mm from the log end.

In the stem bank, CT images of discs cut from the butt end of every log and conditioned to 9% MC are also available. In these pictures, the average sapwood density at 9%, $\rho_{9,9}$, was calculated and used to find a reference value for the dry sapwood density, $\rho_{0,0}$. This value was calculated using the relation between the density, $\rho_{u,u}$, at MC $u$ and the dry density, $\rho_{0,0}$:

$$\rho_{u,u} = \frac{m_u}{V_u} = \frac{(1+u)\cdot m_0}{(1+\alpha_u)\cdot V_0} = \frac{(1+u)}{(1+\alpha_u)}\rho_{0,0} \quad (1)$$

where $m_u$ is the mass, $V_u$ is the volume, and $\alpha_u$ is the volumetric swelling coefficient at MC $u$. The swelling coefficient was calculated using:

$$\alpha_u = \alpha_{\max}\cdot u/u_{\mathrm{FSP}} \text{ for } u < u_{\mathrm{FSP}} \quad (2a)$$

$$\alpha_u = \alpha_{\max} \text{ for } u \geq u_{\mathrm{FSP}} \quad (2b)$$

where $\alpha_{\max}$ and $u_{\mathrm{FSP}}$ are the swelling coefficient and the MC at the fibre saturation point, respectively. The average values for Scots pine were used, $\alpha_{\max} = 14.2\%$ (Esping, 1992) and $u_{\mathrm{FSP}} = 28\%$ (Kollman & Côté, 1968).

By inserting the reference values of the green sapwood density and the dry sapwood density in eq. (1) and using the swelling from eq. (2b), the reference value for the green sapwood MC $u$ was found:

$$u = (1+\alpha_{\max})\cdot\rho_{u,u}/\rho_{0,0} - 1 \quad (3)$$

### *Prediction of sapwood moisture content using the 3D X-ray method*

Industrial 3D and X-ray data for the logs were simulated from the CT images (Skog & Oja, 2010). The simulated data files were then combined using the 3D X-ray technique, and the average green sapwood density of each log was calculated as described by Skog and Oja (2010).

The dry heartwood density 400 mm from the butt end of each log was also calculated from the combined data (Skog & Oja, 2010), and two linear models predicting the dry sapwood density from the dry heartwood density were developed, one model for butt logs and one model for upper logs.

Finally, a prediction of the green sapwood MC was calculated by inserting the average green sapwood density and the predicted dry sapwood density obtained using the 3D X-ray method into eq. (3).

### *Evaluation of results*

A linear correlation between the predicted and the reference sapwood MCs was developed and predictability ($R^2$) and root mean square error (RMSE) were calculated. A threshold value at 145% predicted MC was used to separate the logs into two groups with lower and higher MC, respectively. Calculated MCs were also compared to the theoretical maximum MC for saturated wood (Esping, 1992):

$$u_{\max} = \frac{1560\text{kgm}^{-3} - \rho_{0,u}}{1.56 \cdot \rho_{0,u}} \quad (4)$$

where $\rho_{0,u}$ is the dry mass divided by the green volume. Using eqs (1) and (2b), $\rho_{0,u}$ was expressed in terms of the dry density, $\rho_{0,0}$:

$$\rho_{0,u} = \rho_{0,0}/(1 + \alpha_{\max}) \quad (5)$$

valid for MCs above the FSP. The average value of the swelling coefficient at fibre saturation was used, $\alpha_{\max} = 14.2\%$.

## Results

For all 560 logs, the green density of the sapwood was predicted with a precision of $R^2 = 0.65$ and RMSE = 25 kg m$^{-3}$ (Figure 1). The dry density of the sapwood was predicted with a precision of $R^2 = 0.47$ and RMSE = 43 kg m$^{-3}$ for 553 (98.8%) of the logs (Figure 2). The seven logs that failed prediction were all large butt logs. When combining the predicted green and dry sapwood densities, the sapwood MC could be calculated with a precision of $R^2 = 0.29$ and RMSE = 21% (Figure 3).

The result when using the predicted MC to separate the logs into two groups is shown in Figure 4. The separation between the two groups is not very clear, but all logs with MC below 100% were correctly classified as dry logs. Out of all logs, 70% were correctly classified.

If the MC is plotted against the dry density (Figure 5), it can be seen that most of the observed variation in MC is caused by the varying dry density of the logs. The MC follows a curve of the same shape as the theoretical maximum value (eq. 4), as shown by the solid line in Figure 5.

By comparing the calculated MC to the theoretical maximum, it should be possible to identify logs that have low MC due to drying of the sapwood. Figure 6 shows the ratio between calculated MC and maximum MC. The reference ratio measured in the

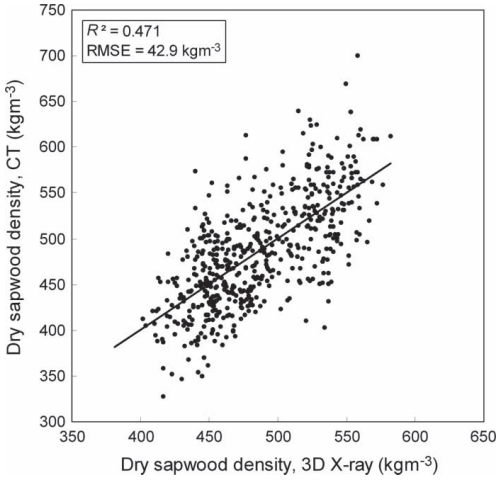


Figure 2. Sapwood dry density in 553 Scots pine sawlogs: measurements in computed tomographic (CT) images versus predictions from simulated X-ray and three-dimensional (3D) log scanner data.

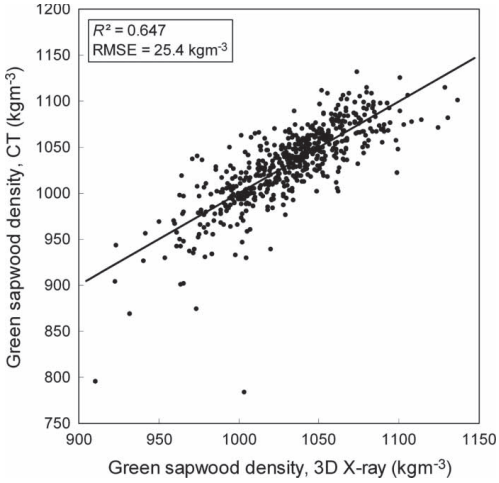


Figure 1. Sapwood green density in 560 Scots pine sawlogs: measurements in computed tomographic (CT) images versus predictions from simulated X-ray and three-dimensional (3D) log scanner data.

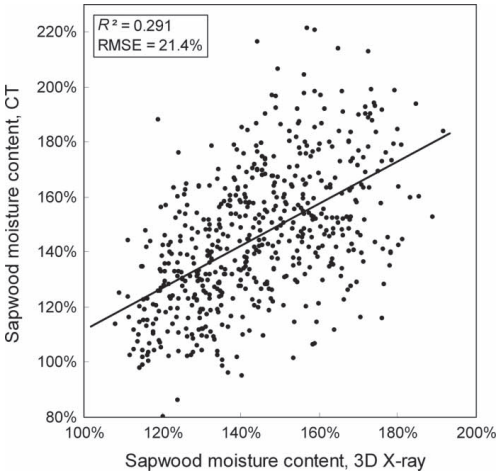


Figure 3. Sapwood moisture content in 553 Scots pine sawlogs: measurements in computed tomographic (CT) images versus predictions from simulated X-ray and three-dimensional (3D) log scanner data.

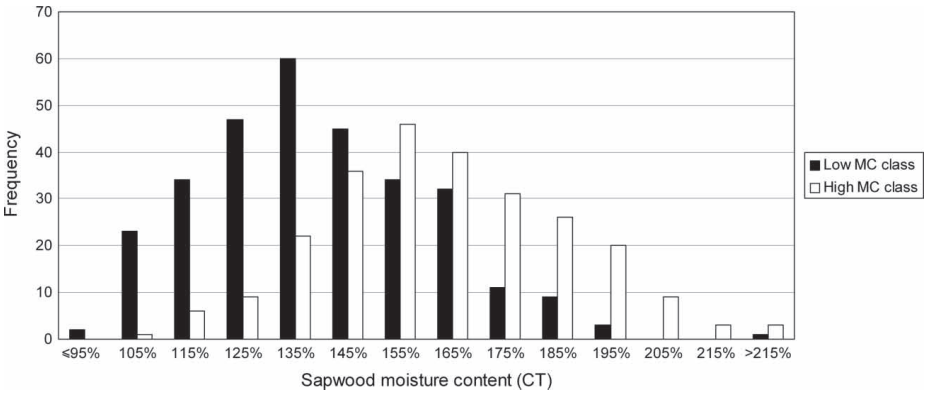


Figure 4. Observed sapwood moisture content (MC) (value from computed tomographic images) for 553 Scots pine sawlogs, separated into two classes depending on the sapwood MC predicted from simulated X-ray and three-dimensional log scanner data.

CT images could be predicted with a precision of $R^2 = 0.39$ and RMSE = 0.036.

## Discussion

For Swedish sawmills, measurement of the sapwood MC would be most useful during periods when the logs may have been stored for extended periods in the forest, e.g. in spring. When the frost goes out of the ground, the roads become very soft and logs may have to be stored *in situ* for several weeks after felling until transport to the sawmills is possible. Because the logs start to dry immediately after felling, sapwood MC may vary significantly between individual logs upon arrival at the sawmill gates, depending on storage time and conditions. This predrying of the logs affects the drying properties of the sawn goods, and many Swedish sawmills need to alter their drying schedules during springtime to avoid problems with cracks and large standard deviations in the final MC. When performing this adjustment of the drying schedules, it would be of great advantage if the raw material could be sorted into batches according to the amount of predrying.

The method developed in this study offers a way of estimating the sapwood MC in sawlogs as they arrive at the log-sorting station. The RMSE of the sapwood MC estimate in the logs, 21.4% (Figure 3), is

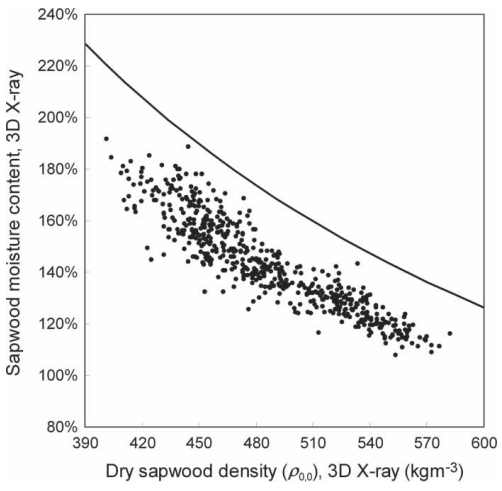


Figure 5. Predicted moisture content as a function of estimated dry density in the sapwood of 553 Scots pine sawlogs. The solid line represents the theoretical maximum moisture content of saturated wood.

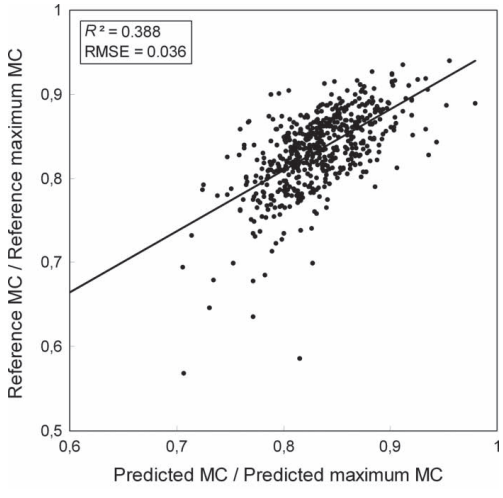


Figure 6. Sapwood moisture content (MC) relative to the theoretical maximum MC of saturated wood: measurements in CT images versus predictions from simulated X-ray and three-dimensional log scanner data for 553 Scots pine sawlogs.

significantly larger than the RMSE obtained when using the alternative method, measurement of the MC in green boards using a microwave scanner (15.9%) (Johansson *et al.*, 2003). However, sorting of logs rather than boards is desirable because it facilitates planning of the production towards batches of optimum size for the kilns. In addition, for sawmills that decide not to sort the logs according to MC, a continuous measurement of the sapwood MC in the arriving logs would be of value, as it provides an important indication about when it is time to start adjusting the drying schedules.

In most of the logs, the predicted and reference values of the green sapwood density follow a linear correlation (Figure 1). For two of the logs, however, the green sapwood density in the reference cross-section is much lower than the predicted log average. This is probably caused by a local drying of the log around the reference cross-section. These two logs are also seen as outliers in Figure 6, with reference values below 0.6.

When predicting the dry sapwood density (Figure 2), seven (1.2%) of the logs failed prediction. These were all large butt logs, which was expected, because for very large diameters, the X-ray signal becomes too weak to be detected. In this study, the dry sapwood density was predicted from the dry heartwood density using linear correlation. Because this relation varies between butt logs and upper logs, two separate correlations were used. For the reference data used in this study, the predictability between dry heartwood and dry sapwood densities was found to be $R^2 = 0.57$. The dry heartwood density, in turn, can be predicted with $R^2 = 0.83$ using the 3D X-ray technique (Skog & Oja, 2010). This means that most of the observed uncertainty in predicting the dry sapwood density ($R^2 = 0.47$) is due to the poor predictability between the dry heartwood and the dry sapwood densities.

When combining the predicted green and dry sapwood densities to find the sapwood MC, the predictability of the reference values was found to be quite low ($R^2 = 0.29$, RMSE = 21%) (Figure 3). Here, it should be noted that the reference values themselves contain some uncertainty. This is primarily because the reference MC was calculated by comparison of the dry density at the butt end and the green density 400 mm from the butt end. Dry CT images were only available at the butt end, but owing to local drying at the log ends, the green density reference could not be taken at the same position. Instead, a position 400 mm from the butt end was chosen for the green CT images to avoid the log end drying, but still to be as close to the end as possible. By choosing this position, the impact of local dry-density variations was minimized. However, especially for butt logs, there may still be a considerable dry density variation over the distance of 400 mm, causing some uncertainty in the reference values used.

The predicted MC was calculated by comparison of a dry sapwood density prediction evaluated 400 mm from the butt end of the log and the average green sapwood density of the whole log. The average sapwood density of the log was used because it was found to be the best available estimate of the green sapwood density 400 mm from the log end. This means that the prediction model tries to predict the average MC in the region around 400 mm from the log end, whereas the reference value is a mixture of two local values taken 400 mm apart. Thus, local variations at the log ends in both dry density and MC contribute to the uncertainty in the prediction of the sapwood MC presented in Figure 3.

Because the correlation between predictions and CT reference values is rather low, the method needs to be verified experimentally. If the green and dry reference densities were calculated for the same piece of wood, the MC references would be more precise, and so the actual amount of uncertainty in the predictions could be determined. Furthermore, testing the method on industrially scanned logs would show that the method is also applicable under industrial conditions.

Because the logs used in this study were all scanned directly after felling, the logs had not dried out, and most logs had an MC around the threshold value of 145% that was used for separation of the logs into groups in Figure 4. Thus, the separation between the two groups was not very clear. Figure 5 shows that most of the observed variation in MC was caused by varying dry density of the wood and not by drying of the logs. This means that sorting of the logs by MC, as illustrated in Figure 4, is not a good way to find logs that have low MC due to drying of the sapwood. Instead, the calculated MC could be compared to the theoretical maximum given by eq. (4), as shown in Figure 6. Comparing calculated and maximum MCs could prove to be a very useful way of identifying logs that have been stored for a long time before arrival at the sawmill. A proper evaluation of this method would require testing on a more diverse population of logs, containing both logs with full sapwood MC and logs with reduced sapwood MC.

In conclusion, by combining 3D and X-ray scanning in the log-sorting station, it is possible to measure the green sapwood density and to estimate the dry sapwood density and, accordingly, the MC in Scots pine sawlogs. Because the correlation with CT reference values is quite low and the reference itself contains some uncertainty, experimental verification of the simulation results is needed.

The MC estimate could be used to separate the logs into two groups with high and low MC, correctly identifying all logs with low MC as dry logs. Out of all logs, 70% were correctly classified.

The estimate can also be compared to the dry density-dependent maximum MC and used to identify logs that have actually started to dry. However, this approach needs to be evaluated for a population of dry logs, because most logs in this study were of full MC.

## Acknowledgements

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# III

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# Effects on microwave measurements and simulations when collecting data close to edges of wooden boards

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ABSTRACT

Parameters like strength, moisture content, density and grain direction are important when sorting wood according to their individual properties. All those parameters can be correlated to microwave measurements of phase shift and attenuation. Measurements of phase shift and attenuation are, however, affected by the vicinity of a board edge. In this article a simulation of the measurement system is used to create a compensation function for the measurements taken close to edges as if those were taken where no effects of the board edge could be noticed. It is shown, by comparison with real measurements, that by doing this the deviation between the values measured close to the board edges and those measured in the middle of the board is decreased, meaning a higher accuracy can be achieved by using the compensating function.

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## 1. Introduction

Wood is a renewable material that can be used in a wide variation of products and applications. To get the highest possible value out of the wooden products it is important, prior to the use, to be able to characterise and sort the wood according to its specific properties. The earlier a correct classification can be done the better the remaining production chain can be adapted to the specified end product [1].

Of high importance in the wood production chain is the moisture content of the individual board. As wood is a hygroscopic material, its moisture content changes according to the surrounding climate. If the moisture content is not correctly determined after the drying process at the sawmill, there is a risk that problems will arise later when the board is in service [2]. An incorrect moisture content can result in mould growth [3], checks, twisting, shrinkage or swelling [4]. As a last step in the production chain at a sawmill, prior to the distribution to the customers, the boards are sent through a final sorting where the moisture content of each board can be measured. High energy prices and the fact that the drying capacity often is the limiting factor for the production at a mill, causes the drying process to be done in as short time as possible. If the conditioning phase in the drying is absent, or to short, the dried boards will retain a moisture gradient. This gradient will cause subsequent dimensional changes of the boards, especially those that are to be split to panels [5]. To be able to measure this moisture gradient as well as other wood parameters one would like to perform measurements close to the edges of the boards. As the boards usually are cross fed through the final sorting there is also a demand to collect data from the whole width of the board, giving a higher number of measurements to process and therefore a statistically more significant measurement result.

FEM-simulations have previously shown to be a good tool for simulating the interaction between wood and microwaves [6,7]. Simulations are also a powerful tool to use when one wants to develop a measuring device or

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understand the behaviour of an existing system. The ease of making changes in an accurate model is greater than when working with a physical system.

It is well known that diffraction of the electromagnetic field occurs close to edges of a material having a different dielectric constant than the surrounding medium [8]. Simulations are also a good way to acquire the basic understanding of fundamental principles that can be applied to complex materials such as wood, where the deviation between individuals is large. Hence, the hypothesis is that simulations of a system can be used to improve understanding of material behaviour when performing measurements close to an edge of a material. This allows the possibility to compensate the measurements to correspond better with the expected values as if those were gained from measurements of an infinite sample.

## 2. Materials and methods

The measurements were performed using a microwave system consisting of two horn antennas with a wooden sample placed in between. A principal sketch of the whole microwave system can be seen in Fig. 1, for a detailed description of the system used see Schajer and Orhan [9].

To localise the point of measurement, the system used a scattering dipole on which the sample under test was placed, see Fig. 2.

Verification of the linear behaviour of the system was done using four pieces of medium density fibreboards (MDF). Measurements were performed when stacking them on top of each other in different sequences and with different rotations of the fibreboards. This was done to make sure there was no anisotropy within any fibreboard as well as no difference between the different fibreboards.

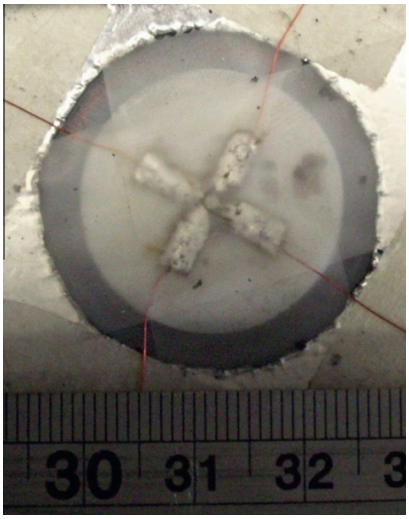


**Fig. 2.** Scattering dipole with two crossed directions used to localise the point of measurement.

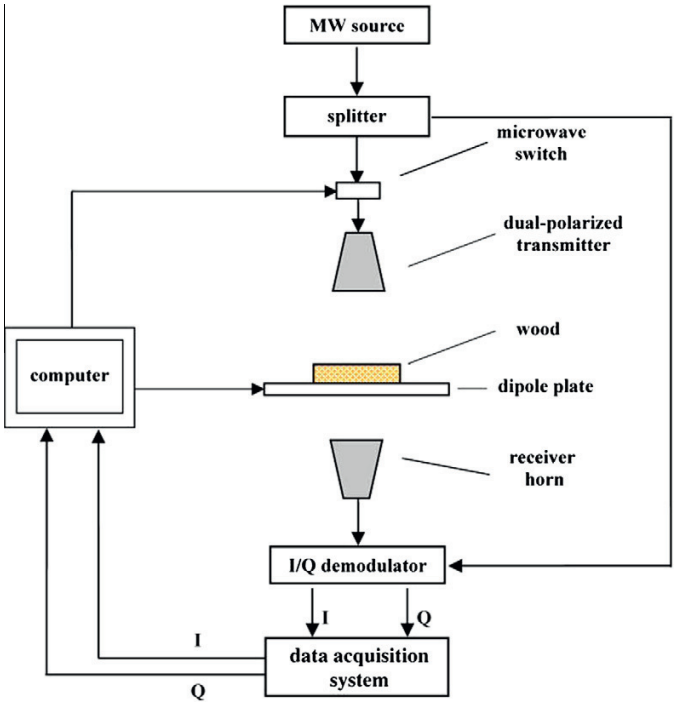


**Fig. 1.** Principal sketch of the microwave measuring device, [10].

In a similar way the linear behaviour of the model was verified by simulation of different thicknesses of a big slab with similar dielectric constant as the fibreboards. MDF was chosen since the dielectric constant is not dependent of the direction within the board, i.e. there should not be any anisotropy since the fibres are in random directions throughout the board.

Nine pieces of well-conditioned wood representing three different density classes with three different thicknesses in each class was used to check the edge effects. Each piece was measured in steps of 2 mm as it was moved over the sensor head. Transmission factors and the phase shifts were calculated in the principal direction of the wood. The principal direction used in the comparisons with the simulated data was from whom the higher transmission factor was achieved, i.e. perpendicular to the wood grain direction. The dielectric constants used in the simulations was taken by linear integration of tabulated values for the same principal direction, i.e. cross grain [11]. To be able to compare the simulated attenuation to the measured transmission factor, a linear regression was done to the measured and simulated values origin from the middle of the board. In this area no effects from the vicinity of the edges could be noticed.

Since the chosen wooden pieces were well conditioned and consisted of clear wood, the assumption was made that the measured transmission factor and phase shift would be uniform within the whole piece. The deviation between the measured result close to the board edge and the stable measurements in the centre parts of the board is therefore presented as an error in the measurements. Measured values are also compensated with the assumption that the measurement shows the same behaviour as the simulations, meaning a compensation of the measured values close to the board edges. All the simulations were performed in COMSOL 4.0a [12].

## 3. Result

Fig. 3 shows the measured and simulated transmission and phase shift near the edge of an example board.

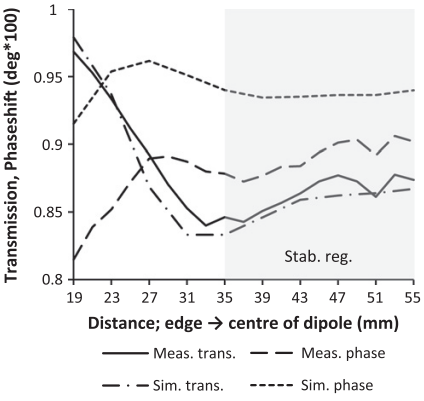


**Fig. 3.** Example of transmission factor and phase shift in the simulations and measurements for one piece of wood.

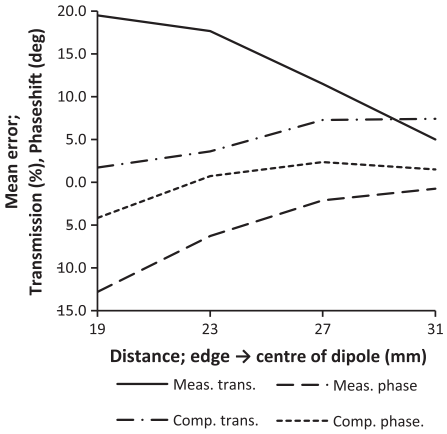


**Fig. 4.** Mean error for the nine measured pieces in percentage of transmission factor and in degrees for the phase shift.

Fig. 4 shows the deviation between the results measured directly and by using a compensation function. The results are compared to the average measured result from the "edge → centre of dipole" distances of 35–55 mm as the measurements where reasonably stable in this area, see Fig. 3. The compensated transmission values were determined by assuming that the simulations and measurements showed the same behaviour, i.e. if the simulations showed a difference between the stable centre values and the value at position 23 mm of 10%, the measured value at this position was changed according to this. The error was in this case calculated as the difference between the compensated value and the average measured value in the stable region.

Compensated phase shift was achieved by comparing the simulated phase shift at a particular position to the average simulated phase shift in the stable centre region and compensate the measured phase shift according to this, i.e. if the simulated phase shift at certain position was 10° higher than the simulated phase shift in the centre region the measured phase shift at this particular position

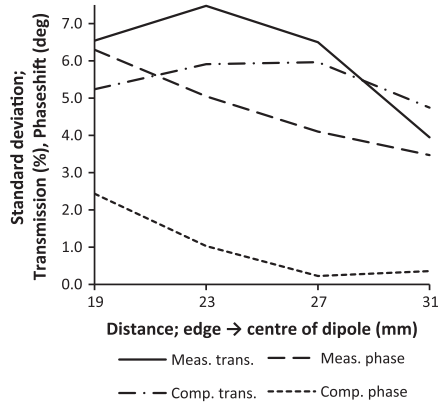


**Fig. 5.** Standard deviation for the nine different wood pieces in the measurements and simulations.

was subtracted with 10° and this, correlated, phase shift was compared to the phase shift measured in the centre region of the board.

In Fig. 4 it can be seen that calibration through simulated values increases the accuracy for the transmission measurements close to the board edges, i.e. for position 19, 23 and 27 mm. The corresponding standard deviation is shown in Fig. 5.

It can be seen in Figs. 4 and 5 that effective compensation can be done to reduce the effects of diffraction on wood parameter measurements made in the vicinity of a board edge by using a correlation function determined by simulating the measurement system.

## 4. Discussion

Performing simulations of a measurement system can become a computationally demanding task. In order to get a reliable result the grid used for the calculations has to be sufficiently small. It is therefore important to consider whether the required solutions can be found by only simulating a small part of the system, as in this case only the edge of the wood. It is also important to point out that it is not straight forward to take the results of the measurement and simulations shown here and use in another measuring system since each system interacts differently with its surroundings. The process of simulating and investigating the effects on the electromagnetic field when performing measurements close to an edge can however be used to increase the practical measuring range of any device.

From a practical point of view, a volume is always being measured rather than a point. This makes comparisons between simulations and real data somewhat difficult and a source of error that is not taken into account in this work. With a setup as described here, the measured area approximately equals the dipole size [13]. A useful method to compare simulated and measured data and not have to struggle with this problem would be to match the achieved curves according to their shapes.

Measurements has shown significant variations in dielectric constants even within the same species, density, moisture content and temperature [11]. Instead of using measured transmission in wood to make it possible to compare simulated attenuation with measured transmission factor it would be sufficient to use different materials, not necessarily wood, with well-defined dielectric constants. It would also be sufficient if those materials spanned a larger space of dielectric constants. Due to the small number of pieces used in this investigation, the difference in the magnitude of the dielectric constant between the individual pieces is a significant source of uncertainty.

It is interesting to notice, that even if the number of tested samples are small and the actual dielectric constant is a matter of concern, the simulated results and the measurements show similar behaviour. Especially the shape of the phase shift values for different distances to the board edge shows a good agreement for the whole range of sample positions. Except for the uncertainly in the magnitude of the dielectric constant, the fact that the wooden samples were not completely isotropic could partly explain the deviation between the simulations and measurements.

Throughout the measurements it was difficult to prevent unwanted reflections from entering the receiving antenna. This problem could be reduced by having the antennas placed closer to each other. Shorter distance between the antennas will however imply that one is working in the near field of the antennas where the electromagnetic field is less well described [14].

## 5. Conclusion

It is shown that effective compensation can be done to reduce the effects of diffraction on wood parameter measurements made in the vicinity of a board edge. This is done by using a correlation function determined by simulating the measurement system. The major advantage is the opportunity to make a higher number of reliable measurements as well as a better chance to measure moisture gradients in the boards, i.e. wet cores.

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# IV

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# MOISTURE CONTENT MEASUREMENT IN SCOTS PINE BY MICROWAVE AND X-RAYS

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## ABSTRACT

There is a demand in the Swedish sawmill industry to improve the accuracy of moisture content (mc) measurements, both to obtain a better tool to run production and to ensure that the products meet customers' expectations. In this study, 240 well-conditioned pieces of Scots pine (*Pinus sylvestris*), sorted into five different groups by visual inspection, were measured using microwaves and X-rays. Models to predict the mc of the wood were made by measurements of an additional 45 pieces of wood.

Using only the measured quantities from the microwave system, i.e., attenuation and phase shift, the root mean square error (RMSE) of the estimated mc was 1.00%. By adding the total density from the X-ray measurements, the RMSE of the estimated mc was lowered to 0.89%. The mean errors of the different wood groups varied from -0.65 to 0.18%.

**Keywords:** *Wood, Inline, Attenuation, Phase shift, Knots.*

## INTRODUCTION

Higher production speeds and a reduced time from the felling of trees in the forest to the final product, driven by both economic and qualitative factors, have led to an increased demand during the last few decades for accurate and automated measuring devices. Because wood shows great variations in properties between individuals and even within the same individual (Dinwoodie 2000), this task has proven to be a challenge. Nevertheless, it is important to obtain as high a value as possible out of the wood to sort the wood to the best-designated end products and to ensure that the quality demands of the end product are fulfilled. Moisture content (mc) is one quality factor that is important in the production chain and in the final use of the wood (Esping et al. 2005). Industrial tests of commercial inline mc meters have shown a low accuracy from individual readings (Esping 2003; Nilsson 2010). All of the different methods for measuring mc have their pros and cons, and most of today's mc meters only use one measuring technique (Vikberg 2010). Nilsson (2010) demonstrated that the accuracy of mc measurements can be improved by taking the visual properties of wood into account. Because sawn wood is often sorted according to different qualities by visual methods, for example, using parameters such as the number of knots, knot size and wood defects, it would be straightforward to use this information together with the mc measurements.

Microwaves have been widely used to predict different wood parameters (Schajer and Orhan 2006; Schlemm 2004). A high microwave frequency gives high-resolution measurements, but one needs to be aware of the risk of the phase shift exceeding $2\pi$ (Hansson et al. 2005). However, if the density of the wood is known, it is likely that a model will be able to predict the number of multiples of $2\pi$ that the phase shift has expired. One way to achieve high-resolution density measurements of wood is by the use of computer tomography (CT) (Lindgren 1992).

This work considers mc measurements using only microwaves and combining these measurements with density measurements performed with a medical CT-scanner. The tested material was manually sorted into five different groups based on its visual properties, and the potential for increased accuracy in mc measurements is discussed according to the results.

## MATERIAL AND METHODS

The tested material consisted of 195 pieces of Scots pine (*Pinus sylvestris*) planed on four sides to dimensions of 44 x 120 x 920 $mm^3$ (R, T, z). The pieces were chosen to represent different kinds of wood, and they were divided into the groups "Normal", "Fine", "Knot",

"Check" and "Defect" by visual inspection. Each group was found in two different mc classes, conditioned to mc of approximately 13% and 16%. The characteristics of the different groups are as follows: the "Defect" group contained large wood defects, such as top rupture and spike knots; the "Knot" group contained considerably large sound knots; the "Check" group contained checks that were easily discovered with the naked eye; the wood classified as "Fine" had very few and small knots, and most of the samples had a high amount of heartwood and an average dry density higher than the other groups; finally, the "Normal" wood was chosen to represent the most common wood at a normal production site. From an end users viewpoint, the group "Fine" would be suitable for window frames, "Defect" would be suitable for packaging and the other three groups would normally be used as construction lumber. The typical magnitudes of some of the characteristic properties of the different groups were measured and are presented in Table 1.

**Table 1. Typical magnitudes of some of the characteristics of the wood in the different groups. The abbreviations are as follows: Cl=Check length, Cw=Check width, Kw=Knot whirls, Kd=Knot diameter, Fd=Fibre disturbance, $\rho_{0,u}$=density of dry wood at moisture content u. Only the central 0.6 m of each board is considered in the table because this was the part of the board where the actual measurement took place.**

| Group | Cl (mm) | Cw (mm) | # Kw | Max Kd (mm) | Fd (mm) | $\rho_{0,u}$ (kg/m$^2$) |
|---|---|---|---|---|---|---|
| Normal | 0 | 0 | 1.7 | 23 | 0 | 400 |
| Fine | 0 | 0 | 1.3 | 7.5 | 0 | 450 |
| Knot | 0 | 0 | 2.2 | 34 | 0 | 400 |
| Check | 430 | 0.5 | 1.5 | 11 | 0 | 430 |
| Defect | 0 | 0 | 1.5 | 21 | 160 | 400 |

All of the pieces were measured with a Satimo microwave equipment using a frequency of 9.375 GHz (Johansson 2001). The measured quantities were attenuation and phase shift in two directions of polarisation, corresponding to parallel and cross-grain. The influence of the dielectric properties of the wood on the attenuation and phase shift of microwaves is described by Hansson et al. (2005), while Schajer and Orhan (2005) describe a method to measure these quantities. The wood density, $\rho_{u,u}$, where u is the mc of the pieces, was measured with a medical CT-scanner (Siemens Somatom Emotion Duo), as described by Lindgren (1992).

During the measurements with the microwave equipment, the short ends of the boards were placed on metal supports, giving rise to some disturbance of the measured values within the vicinity of the supports. Therefore, only data from the central 0.6 m of each board were used for further analysis. To gain an idea of the visual appearance of the boards'

characteristics, three representative boards out of each group are shown in Figure 1 to Figure 5. In the figures, only the parts of the boards where data were collected, i.e., the central 0.6 m, are shown.

**Figure 1. Three characteristic boards from the group "Normal".**

**Figure 2. Three characteristic boards from the group "Fine".**

**Figure 3. Three characteristic boards from the group "Knot".**

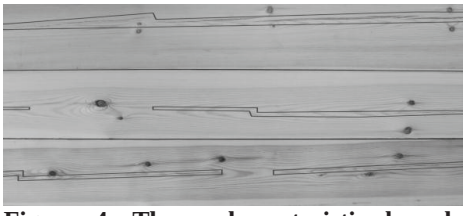

**Figure 4. Three characteristic boards from the group "Check". Because the checks are difficult to see in the picture, they are surrounded by black lines.**

**Figure 5. Three characteristic boards from the group "Defect". Note the grain deviations in large areas.**

Before the wood pieces were removed from the conditioning chambers, each piece was sealed with glue at the ends to prevent drying in the longitudinal direction. Additionally, all of the boards were wrapped in plastic together with other boards from the same mc class to prevent large changes in the mc.

As a calibration set, 45 pieces conditioned to three different mc classes of approximately 8, 13 and 16% were used. The characteristics of the wood used for the calibration were the same as for the group "Normal". The calibration set was kept relatively small to correspond to an industrial calibration procedure. The mc, used as the reference, of each individual piece was achieved using the oven dry method as stated in the European standard: EN 13183-1 (CEN 2002).

The measured data were analysed by constructing a partial least square (PLS) regression model using SIMCA (Eriksson et al. 2006). Multivariate data analysis has already shown great potential and has been widely used in wood research (Danvind 2002; Lundgren and Hansson 2007). Two principal

components were used in the model to span the space to describe the significant relationships in the data. The 45 calibration boards were used for constructing the model, and the prediction of the mc for the remaining 195 pieces was analysed. In the first model, the measured phase shift and attenuation in the two directions of polarisation by means of microwaves was used; the second model also included the mean density from the CT measurements.

## RESULTS

The results from the model predicting the mc from the measured attenuation and phase shift in the two directions of polarisation by means of microwaves are shown in Figure 6.

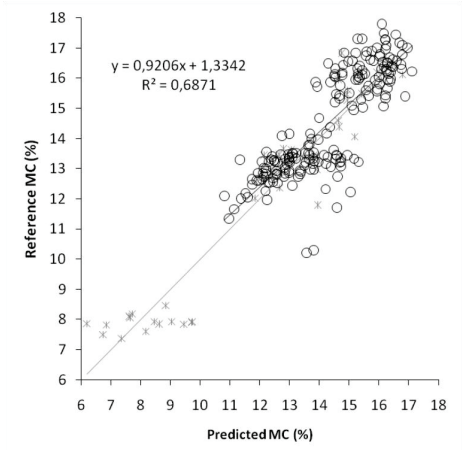


**Figure 6. Predicted moisture content with a model based on the measured microwave attenuation and phase shift. The stars represent the calibration boards, and the circles represent the boards for which the moisture content is predicted. The equation in the plot is a linear least square fit to the prediction set.**

The calibration set in Figure 6 had a coefficient of determination (Montgomery et al. 2004), $R^2$, of 0.92 and a root mean square error (RMSE) of 0.90%. The prediction set had an RMSE of 1.00% and, as can be seen in Figure 6, an $R^2$ of 0.68.

To obtain more accurate mc measurements, the measured wood density, $\rho_{u,u}$, from the CT was used together with the microwave measurements. The result is shown in Figure 7.

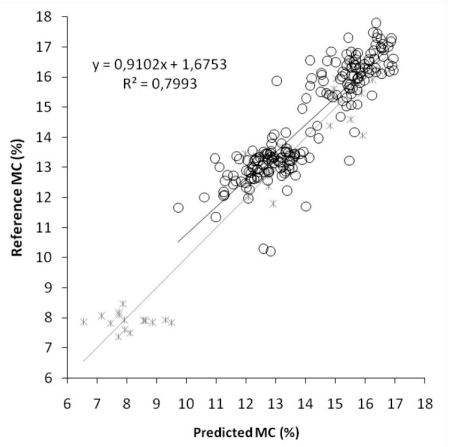


**Figure 7. Predicted moisture content with a model based on the measured microwave attenuation and phase shift with the density from the computer tomography measurements included. The stars represent the calibration boards, and the circles represent the boards for which the moisture content is predicted. The equation in the plot is a linear least square fit to the prediction set.**

The linear regression of the calibration boards in Figure 7 had an $R^2$ value of 0.94 and an RMSE of 0.77%. The different slopes of the regression lines of the calibration and

prediction set show that the calibration was not suitable for all pieces of wood. The RMSE of the estimated mc was 0.89%.

To gain an idea of the possible improvements in the mc measurements by also using an optical device, the mean error and the RMSE are presented for the five different groups of wood. The result is shown in Table 2.

**Table 2. Mean error and root mean square error of the moisture content measurements for the five different groups of wood. The table shows the values when only microwave measurements were used and when they were combined with computer tomography measurements. The two last columns show the root mean square error after subtracting the mean error for each group, i.e., the best possible result if combining the measurements with a visual system.**

| Group | $\bar{\varepsilon}_{MW}$ | $\bar{\varepsilon}_{MW,CT}$ | $RMSE_{MW}$ | $RMSE_{MW,CT}$ | $RMSE^{*}_{MW}$ | $RMSE^{*}_{MW,CT}$ |
|---|---|---|---|---|---|---|
| Normal | -0.65 | -0.55 | 1.06 | 0.85 | 0.84 | 0.64 |
| Fine | 0.18 | -0.21 | 0.64 | 0.61 | 0.62 | 0.58 |
| Knot | -0.36 | -0.37 | 1.06 | 0.95 | 1.00 | 0.87 |
| Check | 0.17 | -0.33 | 1.03 | 0.84 | 1.02 | 0.78 |
| Defect | -0.31 | -0.59 | 1.12 | 1.13 | 1.08 | 0.97 |
| All wood | -0.20 | -0.41 | 1.00 | 0.89 | 0.92 | 0.78 |

As seen in Table 2, the RMSE is the smallest for the most valuable wood, i.e., group “fine”.

## DISCUSSION

It is shown that the RMSE is decreased by adding density measurements determined by CT-scanning to the microwave measurements. Adding a third measurement technique would presumably improve the results even further. Because the mean errors differ between the wood type groups, a visual system would also improve the overall accuracy. If the measurements of a board are taken along the whole length of the board, one can filter out regions where the signal is stable, which implies that no disturbances such as grain deviation or knots are present. In most cases, however, the boards are cross-fed through the final sorting stations where the mc should be measured. In this case, connecting a visual system to the mc meter would be beneficial for detecting objects that are within the meter’s measuring range, thus affecting the measured quantity.

In the prediction set, there are two points with considerably low reference mc. This result is strange because these boards were placed in the same climate chamber as the rest of the pieces in the 13% mc class. There may be some errors in the reference values for those two individuals; excluding them from the prediction set would, however, not produce a remarkable change in the accuracy of the prediction model.

In this work, the board thickness was not taken as a parameter in the model

because the boards were planed to the same dimensions. This step should normally be done because the measured microwave values are related to the wood and water surface density (kg/m$^2$), i.e., the thicker the board, the greater the attenuation and phase shift. A large attenuation caused by either high-density wood, high mc or thick boards limits the use of the described system. As a rule of thumb, the limit is an mc of approximately 20% for a 50-mm-thick board with a dry density of 500 kg/m$^3$. The vicinity of the board's edges will also cause diffraction of the field, and measurements originating from those areas will be difficult to interpret correctly.

An industrial calibration procedure could be simplified if only one board dimension could be used together with pre-programmed correlations for other dimensions. This conclusion is made because there were problems with the calibration in this work, though only a single dimension with well-defined wood was used. Calibration procedures could also be simplified by using calibration dummies with well-defined dielectric properties.

In summary, this study shows that the accuracy of mc prediction was increased by combining microwave measurements with CT measurements. The mean error also differed between the wood type groups, showing the potential to further increase the measurement accuracy by adding a visual system.

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