MASTER'S THESIS

Evaluation of three in-line wood moisture content meters

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Wood Engineering

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Preface

This master thesis is a part of BAT (Best available technology), within the main project PAFF (Produktanpassad virkestorkning: förbättrad fuktmätning och säkrad produktkvalitet – Product adapted wood drying: improved moisture measurements and secured product quality)

There are several persons I would like to show my gratitude to. Without their help and guidance I would be stumbling in the dark and this thesis would be impossible to do. First, I would like to give a big and sincere thank you to my supervisors Lena Antti (LTU) and Thomas Wamming (SP Trätek) for their support and guidance and for the opportunity to do this master thesis. Thanks to Tommy Vikberg for interesting conversations, tips and help. I also want to thank Birger Marklund for showing me how to use the CT-scanner. Last but by no means least, a huge thanks to all the staff at SP Trätek in Skellefteå.

Skellefteå in October 2010

Martin Nilsson

Sammanfattning

Visionen om trä som ett ingenjörsmaterial och ett självklart förstahandsval vid byggnationer, konstruktioner och möbelproduktion ställer höga krav på mätutrustning som kan definiera och fastställa kvalitén på brädor och plank. Fuktkvoten i trä är en kvalitéfaktor som alltför ofta är bristfälligt beskriven vid leverans av sågade varor, men likväl är mycket viktig vid vidareförädling.

Detta examensarbete är en del av ett större projekt vars mål är att finna eller utveckla mätutrustning som kan bestämma fuktkvoter mellan 7 till 18 % MC med säkerheten ± 1 % MC med ett 90 % konfidensintervall. Inom ramen för examensarbetet testades tre fuktkvotsmätare för inline bruk. Mätarna skiljde sig sinsemellan med avseende på mätprincip.

Ett provmaterial med fem vedklasser i två fuktkvotsklasser togs fram. Varje klass bestod av cirka tjugo bitar. Syftet med vedklasserna var att påvisa skillnader i hur de olika mätarna hanterade olika typer av ved.

Två av utrustningarna testades i industrin medan den tredje testades i labb-miljö. Mätarna kalibrerades med samma material i intervallet 8-17,5 % MC. Provmaterialet matades sedan igenom och mätvärdena loggades.

Resultaten analyserades med återkoppling till den mätprincip mätutrustningen använde sig av (i de fall då mätprincipen var känd). Resultaten påvisar skillnader mellan metoderna. Den största skillnaden är att den mätutrustning som använder sig av kapacitansmetod visar ett för högt värde på fuktkvoten då densiteten ökar men med bibehållen referensfuktkvot. Detta innebär att om två plankor med samma fuktkvot men med olika densitet skulle mätas med en kapacitansmätare, får plankan med hög densitet ett högre fuktkvotsvärde då denna innehåller mest vatten. Detta beror på att vattnet är det som påverkar träets kapacitans mest.

Vidare visade det sig att mätaren med kortast våglängd (mikrovågor) visade för höga värden i och runt kvistar. Vad detta beror på är oklart, men en möjlig förklaring kan vara att diffraktion uppstår runt kvisten då denna har högre densitet än ren ved.

Överlag visade fuktkvotsmätarna en bra mätnoggrannhet.

Abstract

The vision of wood as an engineering material and a first choice in buildings, constructions and furniture production put high demands on measuring equipment which can define and determine the quality of boards and planks. The moisture content in wood is a quality factor that is all too often badly described when sawn goods is delivered, but still it is an important factor in the further processing.

This thesis is a part of a project, where the objective is to find or develop measuring equipment which can determine the moisture content between 7 to 18% MC with an accuracy of ±1 % (90 % confidence interval). Within the frames of this thesis, three moisture content meters for inline use where tested.

A test material with five wood classes was produced. Each class included approximately twenty pieces. The intention with the wood classes was to find differences between the meters in how they handle different types of wood.

Two of the equipments were tested in industry and the third in the lab. The meters were calibrated with the same material within the span 8 to 17,5 % MC. The test material was then fed through the meters and the values were logged.

The results were analyzed in regard to the measuring technique or method the meter was using. According to the results, there are differences between the methods. The MC meter which is using the capacitance method shows too high values when measuring high density pieces compared to low density pieces with the same moisture content. This is a result of the nature of capacitance, which mostly depends on the amount of water and not the fraction between water and wood.

The results also showed that the meter which used the shortest wavelength (microwaves) measured too high values in and around knots. The reason for this behavior is unclear, but could be explained by diffraction around the knot due to the higher density.

In general, the MC meters showed good accuracy

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1. Introduction

Drying of sawn timber is the most energy and time consuming production step at sawmills, from the log to the finished product. In general, all sawn products from Swedish sawmills are dried under controlled circumstances in artificial drying kilns before delivering. The time required for a drying batch to reach its target moisture content (MC) is depending on several parameters, and normally takes two to seven days. This process is often a bottle neck at sawmills. The most time consuming part of the drying process is the second phase, when all capillary bound water has left the wood and the drying proceeds by diffusion. Final MC heighten by one MC per cent increase the drying capacity with approximately 10%. The water is removed from the boards by evaporation which demands an energy input. Enormous volumes of water are removed annually and the energy used for wood drying in Sweden is about 5 TWh per year (Andersson 2009).

The target final MC in a board is mainly depending on the drying schedule, where initial MC, density and the fraction of heart/sap wood affect the drying time (Esping 1992). Since boards with different features are mixed in a drying batch, the resulting MC will differ between the individuals, and even within the same board. If the MC of all individuals in a dried batch is measured, the result can be considered as normally distributed with an average value and a standard deviation. The “ten per cent rule” is a suitable generalization of a well dried batch. It means if the target average MC is 15%, the average MC after drying will be 15% ± 1.5% (68% confidence interval) and a standard deviation of 1.5% within the batch. Some individuals will contain unacceptable high amounts of moisture due to the inhomogeneous wood characters. These wet outliers and the variation in MC after drying force the sawmills to dry most of the sawn lumber to a lower average MC than what actually is needed for the further processing or end application. The over-drying is done to make sure that no wet outliers are delivered to the customer.

The drying process is required nearly without exceptions, irrespectively of the further processing and end product. Different types of further processing or end product applications require different final MC. A problem when buying or selling lumber is to establish suitable MC demand specification (Esping 2005). An example of a common demand specification from Swedish building industry is the inadequate “16-18%”. This is an unclear specification and can be interpreted in many ways. Is it the final average MC that should be inside the interval, or is it all the individuals that should be in the interval 16-18%? Another demand specification that is present and used today in for example window manufacturing is the interval 12% ± 2% (SS 81 81 04). According to the standard, all individuals should be within the interval 12% ± 2%. This is not a realistic interval in a technical point of view, since outliers are present in the MC distribution in the dried batch, due to the heterogeneousness of wood. New European standards regarding MC specifications have been written (Esping 2009), but these standards have yet not been accepted by all European wood industries. An implementation of these (new European) standards would simplify the trade and marketing of lumber, both within the boarder and in an international point of view. One of the most important benefits with a common quality stipulation would be assuring the quality whoever the buyer or seller is, and in a long run, the assuring would raise the confidence in the usage of wood.

To fulfil the market demands irrespectively of the standard or agreement in the specification it is important to keep track of the MC after drying. Wrong delivered MC leads to reclamation which is expensive for a sawmill, both in short and long term. An example a long term effect is the pronouncement from the research programme WoodBuild (Nilsson 2009) were they want to decrease the delivered average MC from sawmills to 15% instead of 18% in lumber for building industry, to prevent delivered building material with a MC of 24% or higher. The reason for this is the wet outliers that frequently reach the building industry and cause problem. This indicates that sawmills need to get better in ensuring the quality of their delivered goods. If the sawmills improve their ways to ensure the quality in their wares, they will reach a competitive edge, not only for the sawmill itself, but also for the material wood which would be thought of as a predictable material.

This thesis is one part of a bigger project, where the objective is to gain knowledge, develop methods and techniques which can be used in the production process and result in a better definition of the quality in delivered product quality regarding MC. The take-off point is the “product adapted drying of lumber” concept which means to optimise the drying procedure, in regard to raw material and desired end product. By defining the quality of the delivered lumber the problems with incorrect MC, like variation in dimension, dimension stability will be reduced, and wood would be considered more as a reliable engineer material. One possibility to ensure the moister content of lumber is to control all pieces with an in-line MC meter. In an investigation made by Esping (2003) it was stated that it is possible to measure the MC of all individuals after drying with an accuracy of ± 2.4% (90% confidence interval) with an in-line MC meter. In relation to the standards and demand specifications the accuracy of the tested commercial in-line meters is not satisfying. Further development of in-line meters is therefore a second part BAT (best available technology) in the main project mentioned above. A goal that has been stated in this project is to find, or develop techniques that will make it possible to measure MC with an accuracy of ± 1% (90% confidence interval) within the span 7% to 18%.

There are several benefits in developing and imply in-line MC meters in sawmills. It is highly relevant for the main project to develop the accuracy of in-line meters since it is a suitable way to determine and define the MC of all individuals before delivering, and thereby secure the quality. Apart from defining the MC before delivering, the in-line meter can be used to sort out the pieces with too low or too high MC (Figure 1).

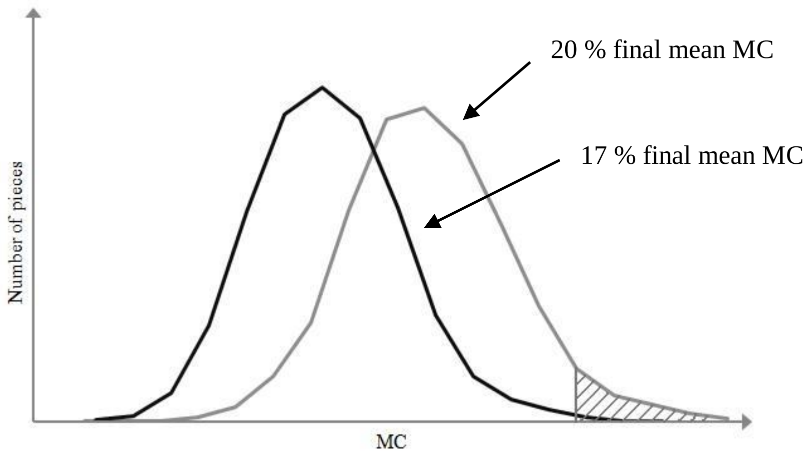


Figure 1: Distribution curves for aimed MC after drying. The grey distribution curve can be attained by the use of a reliable in-line meter. Instead of aiming for 17% MC during drying (black distribution curve), a higher MC will serve as target MC when the wet pieces can be sorted out.

Figure 1 shows a general possible scenario when using a reliable in-line meter. Information about all pieces is achieved and the wet outliers are sorted out. The drying operator can therefore aim for a higher final MC and reduce the over-drying, which otherwise have to be done to eliminate the wet pieces. The benefits in reduced over-drying and higher average MC after drying are:

- Higher yield. Approximately 70% of the costs in a sawmill is the raw material costs. It is therefore vital to always aim for higher yield in the processes. When wood is dried, changes in shape and dimension and sometimes checks arise. The cupping in a centre piece is for example proportional to the MC under fibre saturation point. A higher final MC will reduce the number of pieces that needs to be downgraded due to drying
- Reduced drying time. Drying is the most time consuming step at the sawmill, and it is often the bottle neck. An increased final MC of 3% (Figure 1) can increase the capacity up to 15% (Esping 1992)
- Reduced energy consumption. Approximately 5% less energy will be used if the final MC increases from 17% to 20% (Esping 1992)

A continuous follow-up of all individuals in a drying batch is also a good tool for a drying operator. The information can be used to see how parameters as season, drying schedule and conditioning for example affect the average MC and standard deviation.

It has been made clear that the decrease in over-drying is profitable. By having a well described MC, the quality of the delivered goods is increased. A determined MC is valuable information to wood manufacturers. Too many wood manufacturers buy material and then dry it further to correct MC or to decrease the deviation in MC. The information in MC for delivered goods is in such a scenario a competitive edge for a sawmill and in some cases it should be possible to take a higher price for the product.

A lot of in-line meters were applied in sawmills about 20 years ago with the objective to sort out wet pieces, but the accuracy was not good enough for this purpose. The reason was probably a combination of flawed calibration routines at sawmills and a sensitive equipment to deviation in the measured wood. Four commercial in-line meters were tested by Esping, 2003 and the resulting accuracy was ± 2.4% (90% confidence interval) for the best moisture meter. All tested equipment was based on the capacitance method. Varying density is a high source of error in capacitance equipment. New equipment has been developed and commercialized after 2003. Since it is highly interesting to find or develop a reliable and accurate MC meter, three MC inline meters have been chosen to be tested. The choice was based on the potential to improve the technology that was used in the meters. One capacitance equipment and two new equipment, using microwaves and radio frequency were selected.

1.1 Objective

The objective of this work is to evaluate three MC meters. The evaluation will be the base for the decision on which in-line MC meter (or method) that will be further developed. Three studies are included which will answer the following three questions:

- What is the accuracy of the three inline MC meters when measuring individuals and how well does it fit the goal of ± 1% (90% confidence interval) within an MC interval of 7% to 18%?
- How do different wood features affect the measuring results?
- What is the potential of the three measuring methods in terms of benefits, possible improvements and limitation?

2. Theoretical frame

2.1 Wood and water

Wood is formed in a water saturated environment in the living tree. The living cell walls will remain in this saturated state as long as the roots provide the tree with water. If the tree dies of either a natural cause, or if the tree is cut off, the water transport will be interrupted and the wood will lose most of its water by drying (Skaar 1988).

Wood cells whose function is to conduct water from the root to the leaves are essentially saturated in order to provide the water columns that are not disturbed or broken. When the wood cells no longer serve the purpose as water transporter, the free water in the cell cavity is partial or completely displaced by water in gaseous state. The cell wall itself is still fully saturated with bound water (Skaar 1988). The liquid water in cell cavities is often referred to as “free” water, while water within the cell wall is called “bound” water. This is because it is attracted or bound to the cell wall with stronger forces than the “free” water.

Water in wood occurs in three states; liquid, gaseous and bound state (Figure 2). When wood is dried during manufacturing, all liquid water in the lumen is removed. Some water will remain even after drying, but in the shape of vapour. To what extent depends on the drying and the climate into which the product is later placed. After the “free” water once is removed, it will only recur in the lumen if the product is exposed to liquid water.

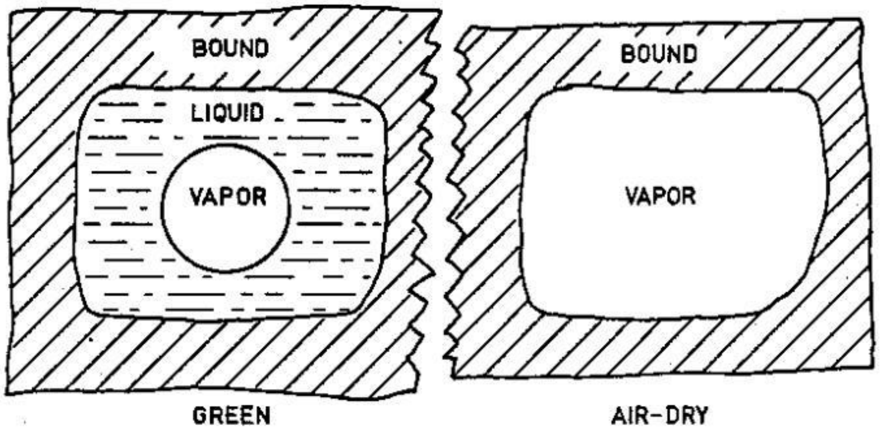


Figure 2: *Illustration of the three kinds of water in green wood and the two kinds in dried wood (Skaar 1988)*

2.1.1 Wood moisture content

The moisture content of wood is often described as a fraction (mc) or per cent (MC) of its dry weight

$mc = \frac{w_w}{w_0}$ Equation 1

$MC = 100 * mc$ Equation 2

where
w_w = Weight of water
w_0 = Weight of dry wood

The percentage (MC) is used for describing moisture content in this thesis. The weight of water is obtained from the difference between the weight of moist wood (w_m) and dry wood (w_0)

$MC = 100 \frac{(w_m - w_0)}{w_0}$ Equation 3

2.2 Interaction between electromagnetic field and wood

The electromagnetic waves are divided into different areas within the electromagnetic spectrum according to its frequency or wavelength. The most common types are shown in Figure 3.

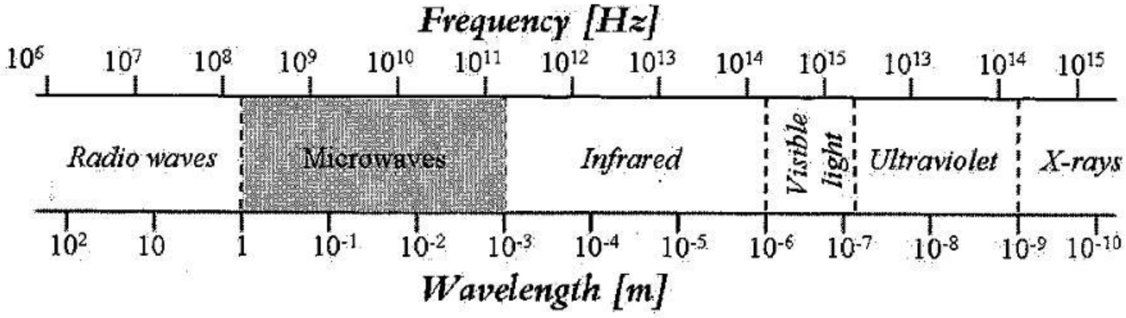


Figure 3: Relation between frequency and wavelength in an electromagnetic spectrum.

Wood is a material with a complex structure and composition. By interacting wood and an electromagnetic field it is possible to find specific properties of the material. The electromagnetic field consist of two components, the electric and the magnetic field. The influence of the magnetic field on wood is negligible and is not taken into consideration for practical use (Torgovnikov 1993). The electric field on the other hand has a strong influence on wood and the interaction results in an electric current in the material.

Under the influence of an alternating electric field the wood reveals its dielectric properties which is well described by the complex dielectric constant (ε*), defined as:

$\varepsilon^* = \varepsilon' - i\varepsilon'' = \varepsilon'(1 - i * tan\delta)$ Equation 4

Where
ε' = the relative dielectric constant (real part)
ε'' = the loss factor (imaginary part)
$tan\delta$= loss tangent, $tan\delta = \varepsilon''/\varepsilon'$
$i = \sqrt{-1}$

Relative dielectric constant (ε') or relative permittivity indicates how much slower an electromagnetic wave propagates through a material compared to propagation in vacuum. The dielectric loss tangent ($tan\delta$) defines the part of the power applied that is absorbed and turned into thermal energy and is correlated to the amplitude of the wave.

2.2.1 Polarization of wood

Oven-dry wood has a specific resistance ranging from 10^{13} to 10^{15} ohm*m and is classified as polar dielectric. With increased MC the resistance is decreased and the conductivity approaches that of semiconductors. Under the influence of an electromagnetic field, the electric properties of wood are explained by the polarization processes that take place due to the interaction between the molecules in wood and the field (Torgovnikov 1993). The summary polarization of wood (P) includes five types of polarization which takes place in moist heterogeneous dielectrics

$P = P_e + P_a + P_d + P_v + P_z$ Equation 5

Where
P_e = electronic polarization
P_a= ionic (atomic) polarization
P_d= dipole (orientational) polarization
P_v= interfacial (structural) polarization
P_z= electrolytic polarization

Electronic and ionic polarization plays the main role when using optical and infrared spectroscopy, but it is not interesting in this context. Within the frequency range 10^5-10^{10} (mostly used frequencies for predictions of wood properties and heating of wood) dipole polarization (P_d) and interfacial (P_v) polarization play the main role in the polarization of wood (Figure 4).

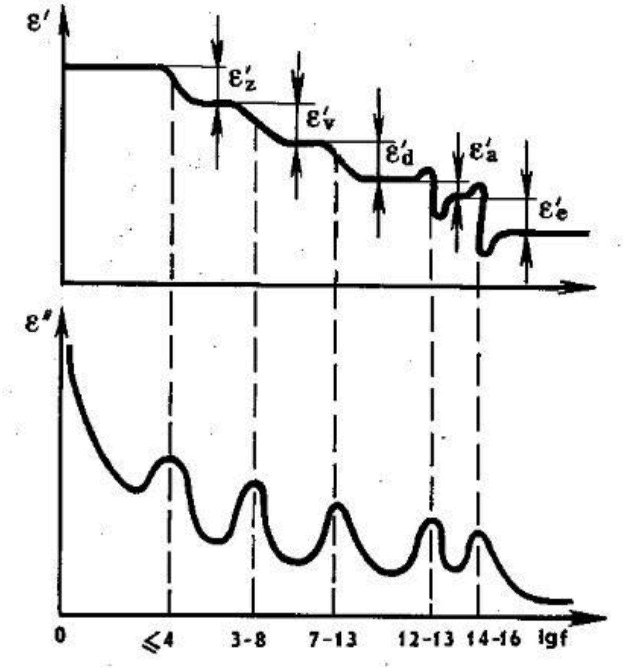


Figure 4: *Schematic diagram of dielectric constant ε' and loss factor ε'' versus frequency response characteristics at different kinds of polarization. Frequency in lg scale (Torgovnikov 1993)*

In the figure above the contribution of different kinds of polarization on dielectric constant and loss factor and at which frequency they occur can be seen. The dipole polarization deposit (ε'_d) manifests itself at frequencies below 10^{12} Hz and above 10^9 Hz. Dipole polarization only occurs in molecules with an asymmetric charge distribution, such as the water molecule (Metaxas 1983). The molecule will change its original orientation and attempt to align with the alternating electric field due to the charges and thereby store an amount of energy. The amount of the stored energy depends on the mass of inertia of the molecule. When the alternating field changes direction (4.9 billion times per second at the frequency 2.45 GHz) the molecules change their position and return the energy to the field. The system behaves like a capacitor. If the used frequency is high enough, the water molecules cannot reach their original state before it is time to change back, because of its relaxation time. Some of the dipole moment of the displaced molecule will in such a scenario not fall back to the electric field. Instead, a part of the energy will be allocated to the molecule in the form of heat. This phenomenon is called dipole relaxation.

The interfacial polarization occurs in heterogeneous dielectric materials like wood and wood-based materials. Wood consists of components in solid, liquid and gaseous phase. Because of the contact difference of potentials between the water and cell wall substance, the water molecules receives a charge of one sign, while cell wall substance assumes a charge of opposite sign. The cell wall substance has considerably less electric conductivity than the water. When adding an electric field, free electrons and ions, which are present in the conductive and semi conductive components in the cell wall, starts moving within the components volume. This results in a dipole moment in the component (Figure 5).

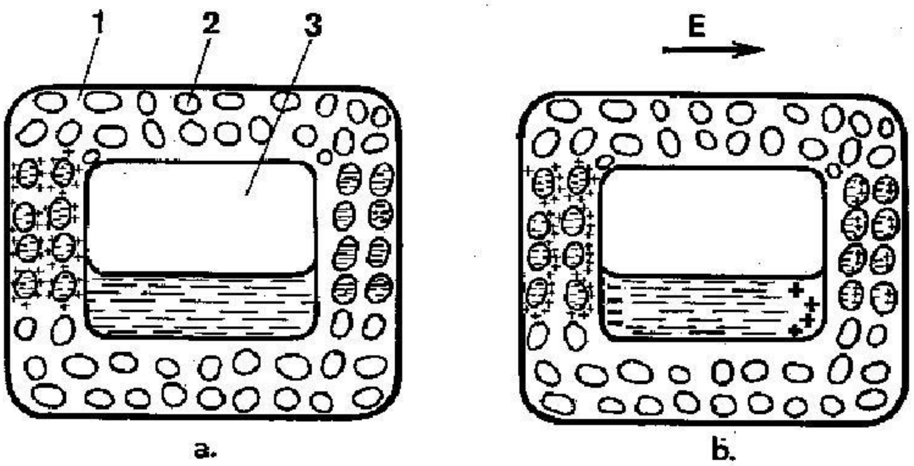


Figure 5: Figure represents a cross section of a wood cell wall. In a, electric field is absent. In b, a current is added which leads to a dipole moment in each component. 1: cell wall; 2: micro fibrils; 3 cell cavity (Torgovnikov 1993)

The interfacial polarization occurs at frequencies within the range $10^3 - 10^8$ Hz.

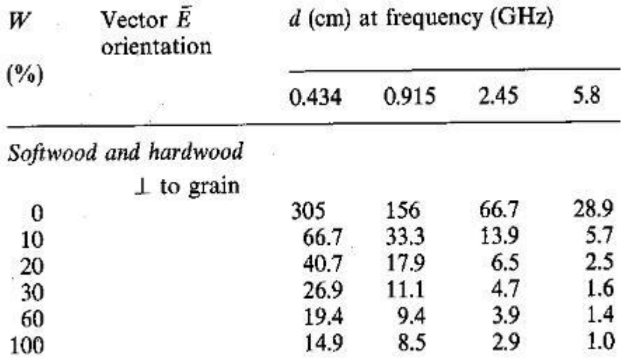
2.2.2 Penetration depth

When an electromagnetic field is penetrating a dielectric material, the electromagnetic energy is absorbed by the material due to the polarity. The electromagnetic field strength at the surface (E_0) is therefore decreasing during the penetration. The attenuation inside the material can be explained by the exponential equation (Torgovnikov 1992)

$$E = E_0 exp(-\alpha X) \qquad \text{Equation 6}$$

Where
α = attenuation constant
X = distance from the surface of the dielectric

Penetration depth is characterized by the distance d from the surface of the board to its inner where the electromagnetic energy has been decreased by $e = 2.72$ times, relative to the energy at the surface (Torgovnikov 1993). Since moist wood absorbs the electromagnetic energy to a higher extent than dry wood does, high MC can be a limitation in applications where the penetration needs to be extended, especially in the microwave span. The absorption is higher when a high frequency is used (Figure 6).



W (%)	Vector $\bar{E}$ orientation	*d* (cm) at frequency (GHz)			
		0.434	0.915	2.45	5.8
Softwood and hardwood					
	⊥ to grain				
0		305	156	66.7	28.9
10		66.7	33.3	13.9	5.7
20		40.7	17.9	6.5	2.5
30		26.9	11.1	4.7	1.6
60		19.4	9.4	3.9	1.4
100		14.9	8.5	2.9	1.0

Figure 6: Penetration depths perpendicular to the grain at four frequencies in the microwave span. MC from 0% to 1 00%, $\rho_0 = {}^{0,5g}/_{cm^3}$ *, t=20°C (Torgovnikov 1993)*

2.3 Measuring MC in wood

Accurate measurement of mc in wood is sometimes harder than it seems. All approaches for MC measuring are based on indirect measuring, which means that a property that depends on MC is measured and not the MC itself. The measured property is then transformed to a MC value through a calibration or calculation of some sort. A measuring method for industry purposes also needs to be fast, apart from accurate and not too expensive.

2.3.1 Oven dry method

The most common version of an oven dry test is stated in the standard ISO 4470. The principal feature is to:

1. Cut a sample of clear wood with a mass of at least 100 g out of the tested board or plank.
2. Weigh the sample with a high resolution scale, and determine the dimensions. It is important to weigh the sample directly after the cutting. The wet density can be calculated by the use of the results.
3. Dry the sample to zero per cent MC in an oven. The temperature has to be 103 ± 2°C and the oven should be well ventilated. When the reduction of mass is below 0.1% per hour, the drying is completed. It is important not to dry the sample too hard, since other substances apart from water can then leave the sample.
4. Weigh the sample in dry state. By the use of the dry weight and wet weight from step 2, equation 3 can be used to calculate the MC.

The oven dry method is used in research, and for spot checks in production, but it is not feasible to test all individuals since the test takes a long time and it is a destructive test. It is possible to chop the tested pieces in smaller cubes to check the moisture distribution within the board. A limitation in the oven dry test is the fact that it is only the MC in the test piece that is tested and not the whole board. But it gives a fairly good determination of the MC in a board, provided the test specimen is cut at least 30 cm from the butt end. The method is otherwise simple and generates accurate results. The oven dry method is also known as gravimetric test.

2.3.2 Resistance method

A resistive MC meter is using the relationship between the resistance of wood and the content of moisture. Two or more pins are hammered into the wood and the resistance between them, or conductivity, is measured by the use of an alternate or direct current. The resistance method generates reliable results under the fibre saturation point only, because other substances such as salt are present in wood above fibre saturation and are affecting the resistance. Below 5% MC, the resistance is too high to make an accurate measurement (Esping 1992). The temperature is also affecting the measuring result. The measured value will be higher if the temperature is high. In some of the resistance meters, the temperature can be adjusted to the actual temperature and the resistance value will be calibrated to give the correct MC.

Continuous or in-line moisture meters have been developed (Figure 7), but the contact free in-line moisture meters were more successful in the market.

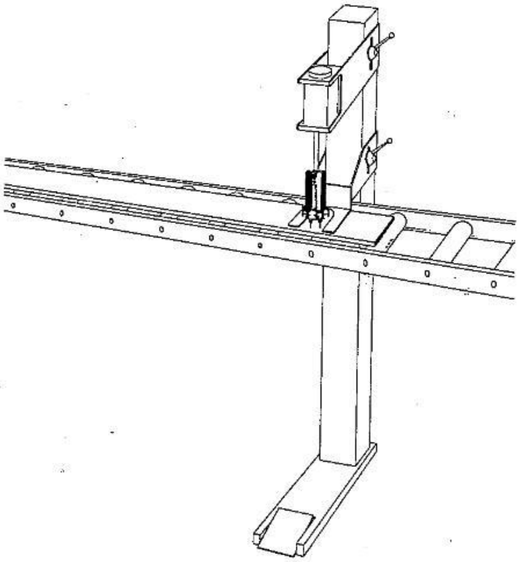


Figure 7: *Continuous MC meter of resistance type. Bollmann Tromatic TM-D1 (Esping 1992)*

The resistance type moisture meter is the most common used hand held MC meter.

2.3.3 Dielectric MC meters

The dielectrical properties of wood are dependent on many parameters. The dielectric constant and the loss tangent change with varying factors, such as amount of extractives and physical properties like specific gravity and fibre orientation, as well as environmental conditions such as MC and temperature. The two parameters that affect dielectric properties the most is MC and density (Figure 8).

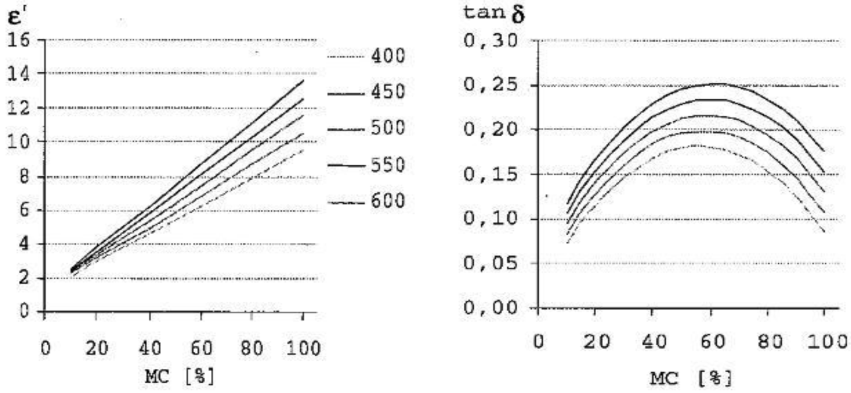


Figure 8: Dielectric constant and loss tangent as function of MC and density at the frequency 2.45 GHz (Antti 1999).

Most of the commercial dielectric MC meters operate at the radio frequency region. Equipment which operates in the microwave region is relatively new. The relationship in dielectric properties and the material properties is also dependent on the frequency used to create the electric field. The dielectric properties of wood and the parameters have been investigated by Torgovnikov 1993. These relations have been applied in industry to measure MC in wood. The technique has been used in both inline meters and hand held meters.

The most common dielectric MC meters in industry today are using the capacitance method. The major part of this kind of equipment operates in the radio frequency region. When measuring MC using capacitance technique, the dielectric constant (ε') is the important factor since this constant is proportional to the capacitance of the material. An investigation was made 2003, where four commercial inline meters were tested (Brookhuis, Exotek, Quasar and Wagner) and it was found that the best of the four meters had an accuracy of ±2.4% (90% confidence interval) and repeatability within 1.8% (Esping 2003). The major drawback with the capacitance method, which affects the accuracy negatively, is the inability to measure the water-wood fraction which makes the method sensitive to varying density in the measured pieces. The capacity is dependent on the amount of water; a high dense piece of wood contains more water than a low dense, despite that they have the same MC. If Brookhuis capacitance equipment is used in a production line where the density is varying, a possibility is to install a density compensator to improve the accuracy. In an older investigation (Eliasson 1989) it was shown that density compensation reduced the mean square error from 2.9 to 2.1.

By the use of two parameters, it is possible to make measurements which are less affected by the specific gravity and thickness. The two parameters are frequency shift which is connected to the capacitance and the attenuation (α) which is correlated to the amount of electromagnetic energy that is absorbed by the material. Since both parameters are dependent on density and MC, it is possible to achieve a ratio which is independent on density and thickness of the measured piece of wood. Another way is to measure the phase shift as capacitance equipment does, but instead of using one frequency, two frequencies can be transmitted to get two density dependent parameters (Zhang 1999). The fraction of the two density dependent values is a density independent measure of the MC.

2.4 PLS Regression

PLS stands for projections to latent structures by means of partial least squares and is used to relate two data matrices X and Y (Höskuldsson 1996). The data is divided into predictors, X data, and responses, Y data (Figure 9). The PLS algorithm calculates the principal components in such a way that the correlation between them is maximized.

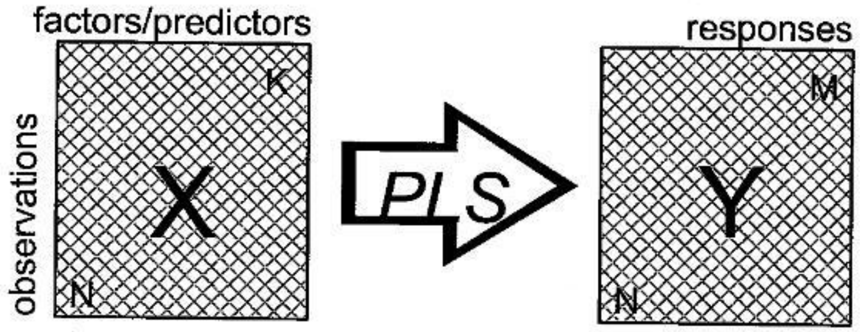


Figure 9: PLS is a method for relating two data matrices X and Y. (Eriksson Et.al 2006)

PLS provides many ways to interpret a model and test its performance and relevance. PLS weight plots makes it possible to gain information about the quantity of impact a predictor (X) is making on the response (Y) (Eriksson Et.al 2006). PLS weight plots are used in the analysis in this thesis.

2.4.1 Interpretation of weight plots

Figure 10 is a weight plot of a dataset containing four X variables (mica, glas, crtp and amtp). The response (wrp2) is circumscribed at the right in the figure. The weight plot in Figure 10 presents the relationship between all factors (X variables) and the responses (Y variables) at the same time. This weight plot shown is an example of how to interpret it. When interpreting a weight plot, one should imagine a straight line through the origin and the response. Secondly, all factors are projected orthogonally onto this straight line (dotted arrows in Figure 10. The position of the projections is important when interpreting the weight plot, since it tells how much the factor is affecting the response and in which way. The projections can be compared to a jigsaw; a factor located close to the origin has a low influence on the response while a factor far from the origin has a great impact.

The two factors glas and amtp are located at the positive side of the origin as the response wrp2. It is therefore concluded that the response is positively related to these two factors.

If the ambition is to decrease the wrp2, glas and amtp should be decreased. The factor with highest influence is mica since it is most far away from the origin. If mica is increased, wrp2 is predicted to decrease because mica is located at the negative side of the origin. Finally, the factor crtp has almost no influence on wrp2 because it is projected close to the origin (0,0) (Eriksson Et.al 2006)

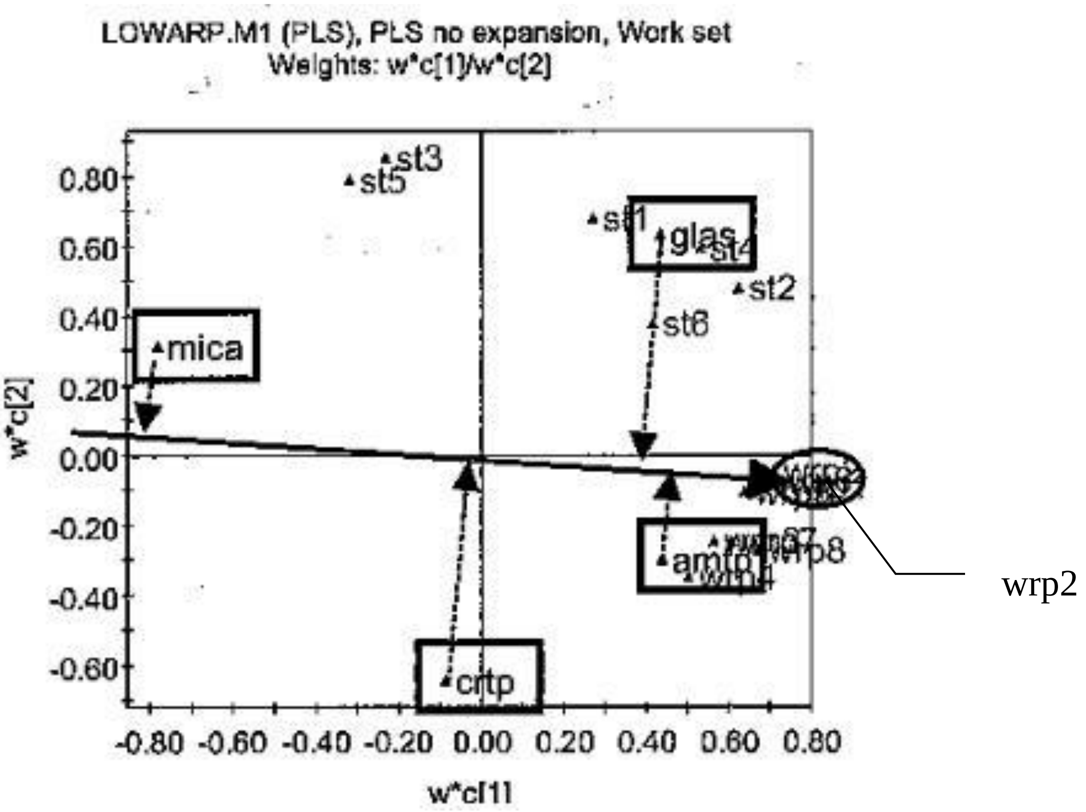


Figure 10: Example af a PLS weight plot. Here used to explain how to make the interpretation. The arrows have been added for educational purpose. (Eriksson Et.al 2006)

3. Material and Methods

Since one of the objectives was to find out how the three moisture meters deals with different MC and types of wood, the test material was designed in accordance to five selected features. The material was divided into two main groups regarding MC level; 14% and 18% MC (Figure 11). Apart from the test pieces, a MC level calibration set was used including 15 pieces at three MC levels. The calibration material consisted of normal wood (explained below) and the wood species was Scots pine (*Pinus Sylvestris*).

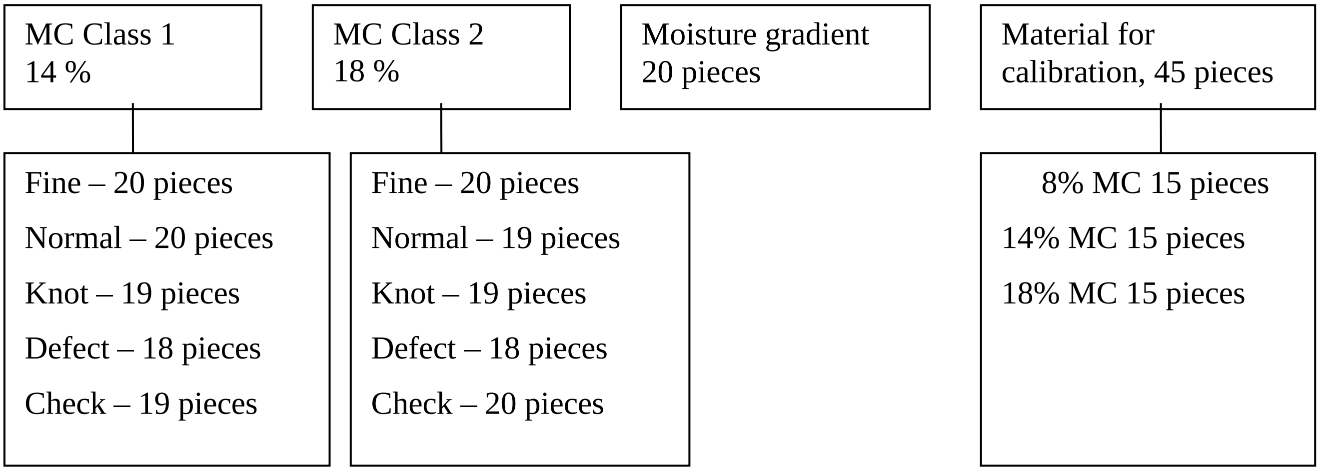


Figure 11: Overview of main groups and wood types in test material

At each mc level five classes containing different wood features were measured. These types were:

Fi-	Fine wood: High quality wood for window manufacturing. These pieces have a high density and high fraction of heartwood.
No-	Normal wood: No sensational characteristics. Low density.
Kn-	Wood with knots: these pieces are characterized by their big tight knots.
De-	Wood with defects: Defects of different characters. Loose knots and fat wood for example.
Ch-	Wood with checks: Varying density and checks.

Figure 12 show one piece from each wood type. Note that the defect piece might not be representative, since the defect type includes several kinds of wood defects.

Figure 12: Examples of wood types, represented in each MC class

The distribution of MC and dry density within each MC class and wood type is presented in Table 1. All test material in the two MC classes originates from two wood manufacturers; Setra and Martinsons The test material from Setra (Lövholmen) has high density and has been sorted out to fit the high standards of window production. They also have a high fraction of heartwood. This material was used in the wood type fine group. The material from Martinsons (Kroksjön) was sorted out according to its wood features.

Table 1: Average value and deviation for MC and dry density of test material

Group	**Moisture content**		**Dry density**			
	Average (%)	s	Average (%)	s	n	Origin
14Br	13.9	0.4	404.0	22.7	19	Kroksjön
14De	14.2	0.3	422.1	44.4	18	Kroksjön
14Fi	13.8	0.4	453.6	28.4	20	Lövholmen
14Ch	14.2	0.4	458.9	57.3	19	Lövholmen/Kroksjön
14No	14.2	0.3	395.1	25.9	20	Kroksjön
Total	14.1	0.4				
18Br	17.7	0.5	388.6	22.8	19	Kroksjön
18De	17.7	0.6	395.8	40.6	18	Kroksjön
18Fi	17.1	0.3	453.6	27.8	20	Lövholmen
18Ch	17.7	0.7	436.4	49.9	20	Lövholmen/Kroksjön
18No	17.7	0.6	383.9	26.0	19	Kroksjön
Total	17.6	0.6				
Gradient	16.4	1.4	404.4	14.2	20	Ala
Calibration						
8%	8.2	0.4	436.9	40.2	15	Kroksjön
14%	14.3	0.4	418.1	62.6	15	Kroksjön
18%	17.5	0.8	410.0	35.6	15	Kroksjön

3.1 Producing the test material

The production of the test material included five steps or processes (Figure 13:).

Figure 13: The production of the test material included five steps.

Most of the test material was obtained at Kroksjön sawmill (Martinsons), see Table 1. Feasible wood pieces was sorted out and sawn, according to their wood types. The length of the pieces were approximately 1.1 meter, and they were sawn at least one meter from the butt end of the main plank to prevent problems with end drying and the hysteresis effect during the further conditioning.

Conditioning of the test pieces was done in two climate chambers with different climates (Table 2). The actual MC in Table 2 differs from the planned MC, especially for chamber 1. This is probably the result of an unfunctional thrust nozzle in chamber 1.

Table 2: Conditioning parameters and resulting MC in the two climate chambers.

	Chamber 1	**Chamber 2**
Relative humidity (%)	65	85
Temperature (°C)	21	25
Time (weeks)	3	3
Wanted EMC (%)	12	18
Final average MC (%)	14.1	17.6

After the conditioning, all test material was planed to the final width and thickness 46 mm by 120 mm.

All pieces were scanned in a CT-scanner (Siemens Somatom AR.T.) to get as much information about the test material. A picture of the cross section was taken every 10 mm of the scanned specimen length.

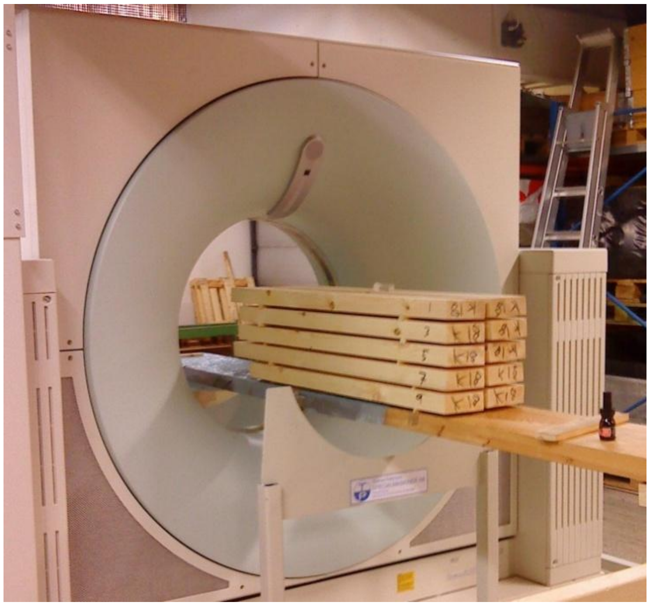


Figure 14: All pieces were scanned in a CT-scanner (Siemens Somatom AR.T.).

The MC, wet density and dry density was determined by oven dried tests. 20 mm thick pieces were cut out from the test material. The dimensions were measured with a digital slide calliper, and the mass were determined with a scale (Figure 15). The pieces were then dried to 0% MC in 103°C. After 20 to 24 hours the pieces were considered as completely dry and they were weighed again. MC was then calculated by the use of equation 3.

After the oven dry test, all pieces were wrapped in plastic to prevent moisture uptake.

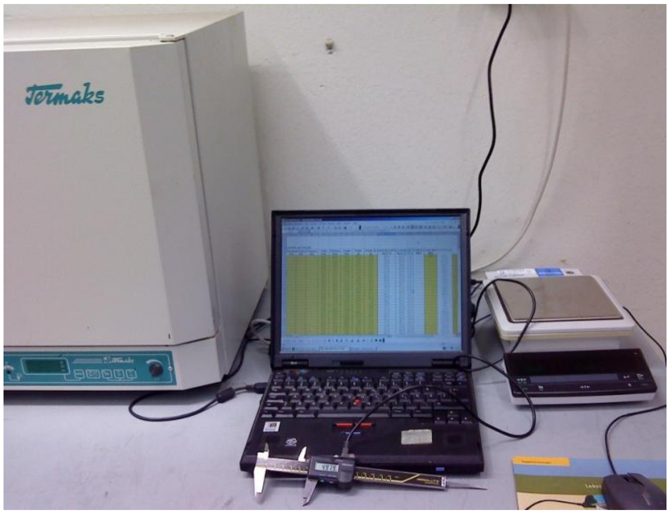


Figure 15: Equipment used for oven dry test.

3.2 Tested equipment

Three different equipment for inline MC measurements were included in this test. All are measuring the dielectric properties of wood in one or another way, but the methods differ between them. Another thing, apart from the measuring method, that differs is the time that they have been available at the market. Note that all tested equipment feed the material longitudinally.

- MiCROTEC M3 scan is an inline MC meter which uses a frequency in the radio span. Details about the equipment; frequency range, signal transformation and equations have not been available. The measured parameters are therefore unknown. However, the dielectric properties of wood are measured in one or another way. The material is fed longitudinally

- The inline MC meter from Brookhuis is a high frequency meter. The equipment has been available at the market longer than the other two tested equipment. The capacitance is the measured parameter. More information can be found at www.brookhuis.com

- Timberscan is a microwave based system for measurement of MC and density of wood inline. It is developed and commersialized by Döscher & Döscher. A microwave resonator is used to generate a resonance frequency (Schlemm 2004). Two parameters are measured which results in a mass independent MC. More information about the design and function of the resonator can be found in the article, Knöchel, Et al. 2007

A resonance curve is characterized by the two parameters, resonance frequency and width of the resonance curve at half level (Figure 16).

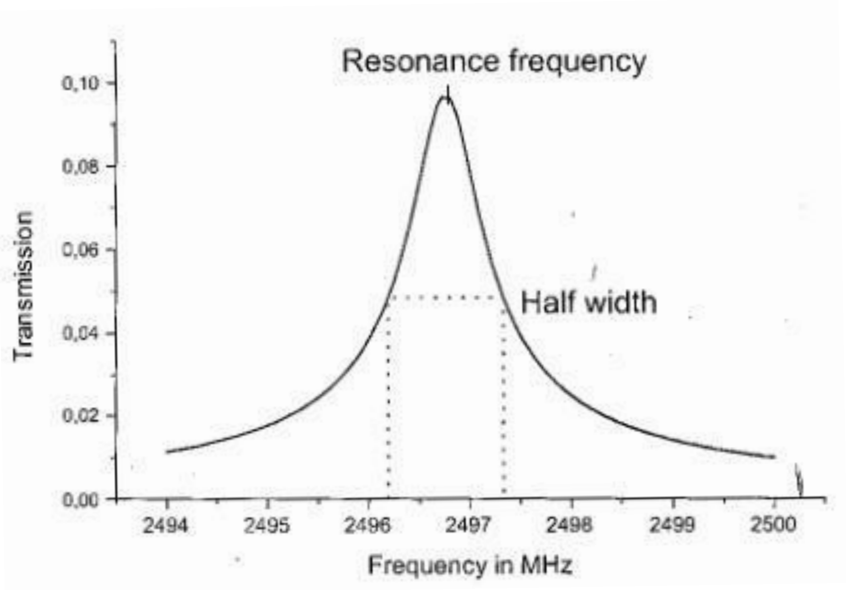


Figure 16: Resonance frequency curve and its parameters, transmission and frequency (Schlemm 2004)

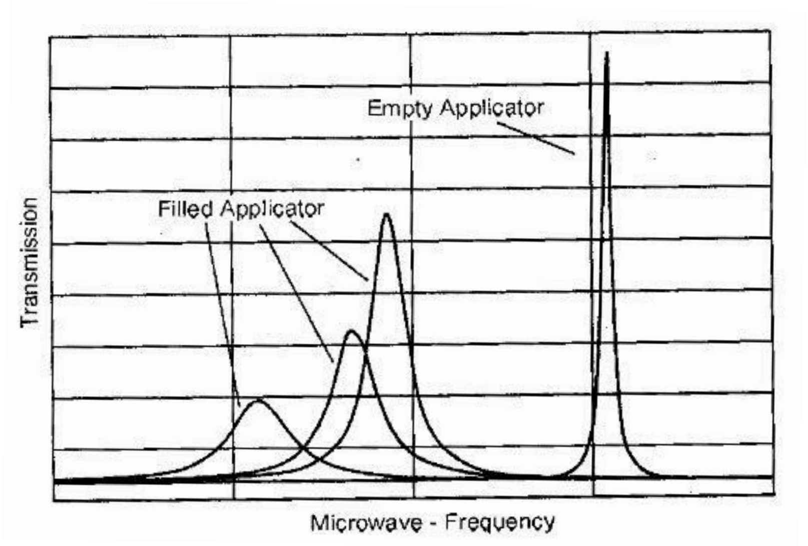


Figure 17: Resonance curves of empty and filled applicator (Schlemm 2004)

When a material is placed in the applicator, the resonance frequency and transmission are changed (Figure 17). The frequency is decreased due to the decrease of the wavelength inside the material and the width at half level is increased due to energy loss in the electromagnetic field.

Water has a strong influence on the electromagnetic field because of its high permittivity compared to dry wood. When both MC and density is varying within the measured material, both parameters have to be considered. The MC is calculated as follows. First, the resonance frequency shift (A) is measured:

$$A = f_0 - f_m \qquad \text{Equation 7}$$

where,
f_0= Resonance frequency of the empty resonator (Hz)
f_m= Resonance frequency when the applicator is filled (Hz)

The second parameter measured is the increase of width at half level (B):

$$B = w_m - w_0 \qquad \text{Equation 8}$$

where,
w_m = width at half level of a filled applicator (Hz)
w_0= width at half level of the empty applicator (Hz)

The microwave value (ϕ) is defined as:

$$\phi = \arctan\left(\frac{A}{B}\right)$$ Equation 9

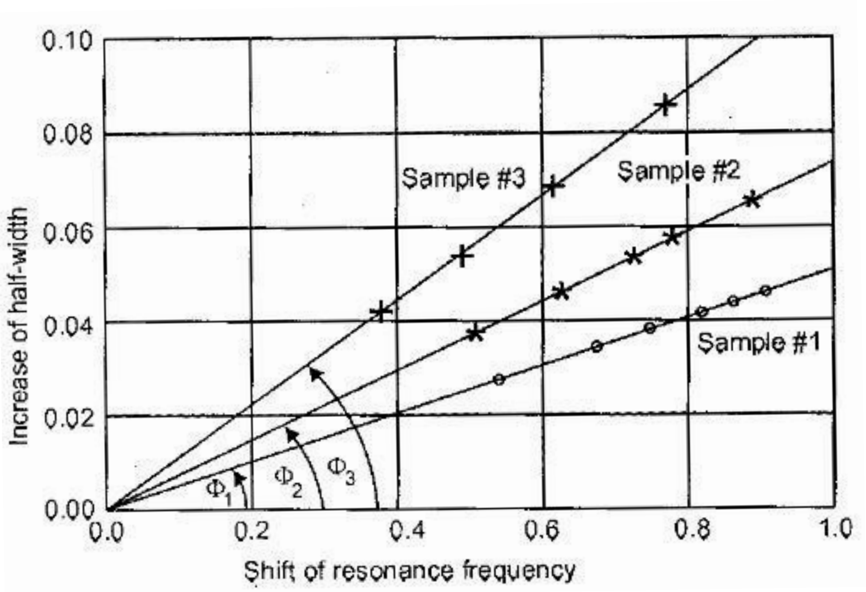


Figure 18: Measured parameters A and B for three MCs and varying mass (Schlemm 2004)

Since both parameters A and B are mass dependent, the fraction only depends on MC. The arc tangent operation is calculated to reduce the codomain of the moisture value ϕ: $\phi \in [0,1], \phi$ which is nondimensional.

In Figure 18, three samples with different MCs are shown. Each sample is measured with varying mass, located in the measuring field. According to Figure 18, the angles ϕ_1, ϕ_2 and ϕ_3 are mass independent.

In most common cases, a linear calibration can be used to transform the microwave value to measured MC in per cent (Schlemm 2004).

$$u = a_1 * \phi + a_2$$ Equation 10

where

u = moisture content in %

a_1, a_2 = calibration coefficients

ϕ = microwave value

A linear calibration can be used within certain limits. For high and low MCs the relation between MC (u) and microwave value (ϕ) becomes nonlinear. These limits for high and low depend on the characteristic of the measured product. A nonlinear calibration curve needs to be used in these cases to receive a correct MC value.

4. Results and discussion

The measurements are first presented in a plot, in relation to MC from the oven dry tests (Figure 19, 23 and 27). There are two straight lines in each plot, one reference line and a trend line. For a perfect set of measurements, all dots should connect to the reference line together with the trend line. A perfect trend line equation has the slope 1 and an offset at 0, and the correlation coefficient 1. The coefficient of determination is calculated and written under the trend line equation. The coefficient of determination is a value from 0 to 1 and indicates how well the data is explained by the equation. Calibration and gradient pieces are not included in the relation plots.

In the relation plots it is not possible to see the deviation and systematic error for different wood types. Histograms for both MC classes are presented after the relation plot to serve that purpose (Figure 20, 21, 24, 25, 28 and 29). Two histograms are presented, one for each MC class. Measuring errors for all pieces in each wood type class is visualised in the histograms.

4.1 MiCROTEC M3SCAN

Two clusters can be seen in Figure 19, MC class 1 and MC class 2. The MC class 2 cluster lies below the reference line which indicates a systematic measuring error. The deviation is low for MC class 2 since almost all measurements are oriented along the reference line. The MC class 1 on the other hand, has a higher deviation but the systematic error is small. The systematic errors could be a result of the wide calibration span (8 – 18%).

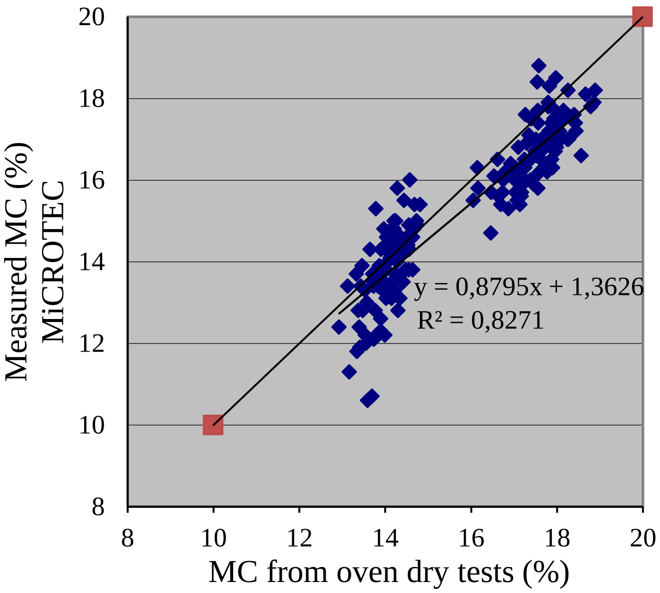


Figure 19: Relation between measured MC and MC from oven dry test

The measurement errors are visualised in histograms in Figure 20 and Figure 21. Here it is possible to see the distribution of measure errors for the five different wood types within MC class 1. An idea of the average measuring error for each wood type can also be made when looking at the staples. Figure 20 show that MiCROTEC made an outstanding measure for the "normal" wood type. The staples are closely gathered around zero, which indicates low measuring error and low average error. The two wood types with high density are distinguished in the histogram because of their negative average error and high standard deviations for the measuring errors. It seems that the equipment has a problem measuring some of the "fine" pieces.

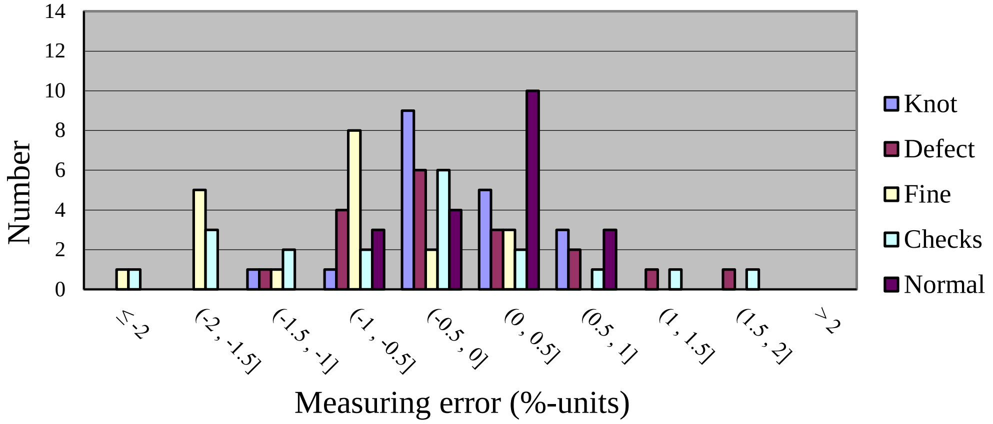


Figure 20: Histogram showing measuring error for all wood types in MC class 1(MiCROTEC)

Not all average errors can be correlated by calibration since there are differences in average error for the wood types. In Figure 20, it is seen that the wood type "fine" is continuously lower than the "normal" wood type for example. The sum of all average error for MC class 1 could possibly be calibrated to a low total average error, using a mixed calibration material.

On the left hand side of Table 3, average errors for the set of pieces in each wood type for MiCROTEC are seen. On the right hand side the average errors have been calibrated to exactly fit the "normal" wood type. The calibration is here perfect for the "normal" wood type. The systematic error is the difference between average error of the wood type and average error of the "normal" wood type. It is not possible to calibrate a systematic error. Since the "normal" wood type was used as calibration material, the average error for this type is seen as a measurement of the calibration quality. High values, positive or negative indicate a low calibration quality.

The "normal" wood type has an average error close to zero (Table 3) which means that the calibration curve fits the MC class 1 well. Note the high negative systematic errors for the wood type "fine" and "check". These two wood types also have the highest standard deviations. One of the goals in the main project is to develop equipment for MC measuring with an accuracy of ± 1% with a 90 % confidence interval. Some of the wood type classes had measuring errors within this interval. “Normal” and “knot” wood types are approved according to the stated interval.

Table 3: Average error, standard deviation and systematic error for MC class 1 (MiCROTEC)

Knot			**Knot**	
Average error (%)	-0.01		Systematic error (%)	-0.04
St.dev	0.54		St.dev	0.54
Defect			**Defect**	
Average error (%)	-0.01		Systematic error (%)	-0.05
St.dev	0.73	Calibration (Normal wood)	St.dev	0.73
Fine			**Fine**	
Average error (%)	-0.91		Systematic error (%)	-0.94
St.dev	0.81		St.dev	0.81
Check			**Check**	
Average error (%)	-0.47		Systematic error (%)	-0.51
St.dev	1.09		St.dev	1.09
Normal			**Normal**	
Average error (%)	0.035		Systematic error (%)	0
St.dev	0.47		St.dev	0.47

The measurement errors in MC class 2 (Figure 21) are more gathered than in MC class 1 (Figure 20), but there is a high negative trend in the average errors. The average error for wood type “fine” and “check” is also here more negative than for wood type “normal”, but not to the same extent as for MC class 1. The histogram below also contains pieces with moisture gradients. The equipment measured these pieces rather accurate, since the staples are gathered together. The difference in average error between “normal” and “gradient” wood type is high and can probably be explained by the thicker dimensions of the gradient pieces compared to the material used for calibration.

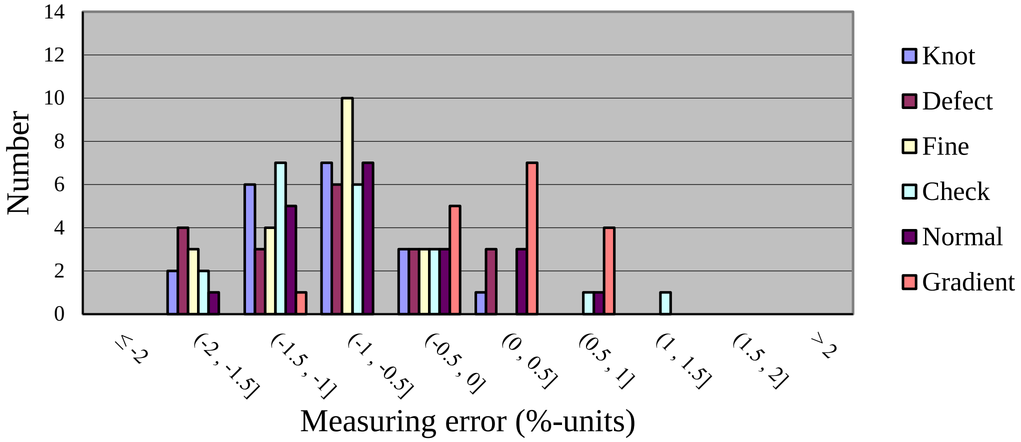


Figure 21: Histogram showing measuring error for all wood types in MC class 2(MiCROTEC)

The systematic errors are lower for MC class 2 than for the previous class. Both classes show low systematic errors for “knot” and “defect” wood type and higher negative systematic error for “fine” and “check” wood type.

Three moisture gradient pieces were rejected from the data because they had higher MC than the upper limit of the calibration that was used, and the values were therefore not trustworthy. None of the pieces in the other wood type classes pass the stated interval for the original calibration.

Table 4 Average error, standard deviation and systematic error for MC class 2 (MiCROTEC)

Knot			**Knot**	
Average error (%)	-0.85		Systematic error (%)	-0.18
St.dev	0.56		St.dev	0.56
Defect			**Defect**	
Average error (%)	-0.82		Systematic error (%)	-0.16
St.dev	0.62		St.dev	0.62
Fine			**Fine**	
Average error (%)	-0.93	Calibration (Normal wood)	Systematic error (%)	-0.26
St.dev	0.45		St.dev	0.45
Check			**Check**	
Average error (%)	-0.75		Systematic error (%)	-0.08
St.dev	0.74		St.dev	0.74
Normal			**Normal**	
Average error (%)	-0.67		Systematic error (%)	0.00
St.dev	0.58		St.dev	0.58
Gradient			**Gradient**	
Average error (%)	0.15		Systematic error (%)	0.82
St.dev	0.50		St.dev	0.50

Due to the high standard deviations in measuring error for wood type “check”, the pieces in this group was sorted in two sub classes, pit-check class and sap-check class. From the PLS weight plot (Figure 22) one can see that these two sub classes are separated from each other, which means that they affect the response (measuring error) in different ways which might explain the high deviation in measuring error. There are some differences between these two sub classes apart from the check location. A pit check occurs when the pit is located inside the board during drying and has not so much to do with other wood parameters such as density etcetera. A check in the “sap side” of a board on the other hand is often related to wood parameters that make the board hard to dry, like high density and high amount of extractives. It is hard to tell the reason for the deviating measure values between these two sub classes since there is more than one wood parameter that differ, plus the fact that the main check class is divided into two smaller classes with a lower number of pieces, which makes it harder to state any statistical conclusions.

The weight plot, Figure 22 is made from a dataset containing information in the test material from the oven dry test, and the measuring results. The difference between reference MC and MC according to the equipment is put as the response (Diff MC). The six types of wood features are dummy variables.

The relation plot (Figure 19) indicates that a high reference MC most often result in a negative measuring error. That is also what the weight plot suggest (Figure 22). The factor MC is the reference MC and since it is located far down in the left corner at the opposite side of the origin, the relation is negative. The high influence of the factor MC is related to the problem in calibration.

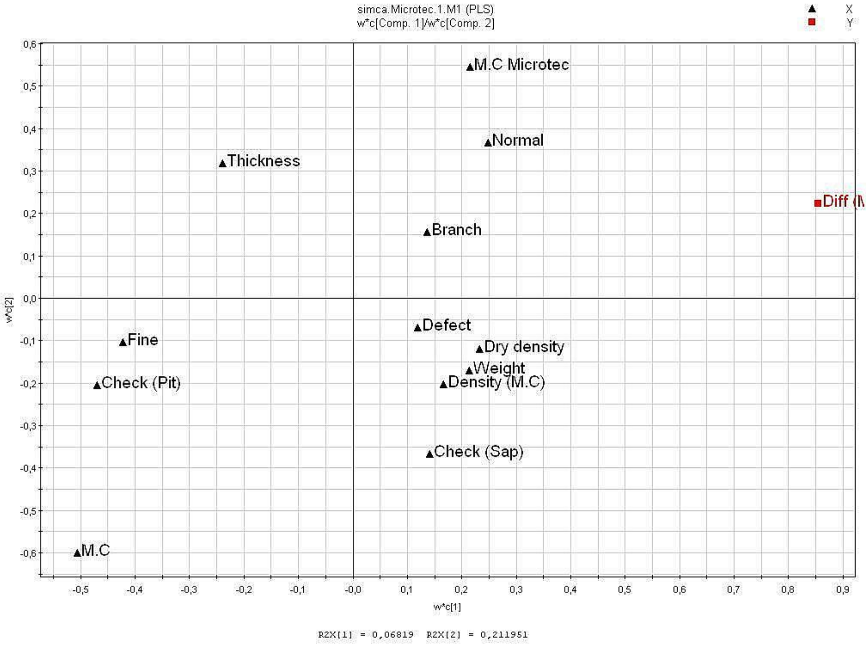


Figure 22: Weight plot with the difference between measured value from MiCROTEC and reference MC as response (Diff (M.C)).

4.2 Brookhuis

Brookhuis show the weakest relation between measured MC and reference material. According to the R^2 value, the measurements are not very well explained by the trend line (Figure 23). The two clusters that can be seen is MC class 1 (14%) and MC class 2 (18%). Nearly all dots are lying under the reference line, which denotes a not satisfying calibration. Probably it is the wide calibration span that causes the high negative average errors, which are especially high in MC class 2. The moisture gradient pieces are not included in the relation plot, since not all of the tested equipment included these pieces.

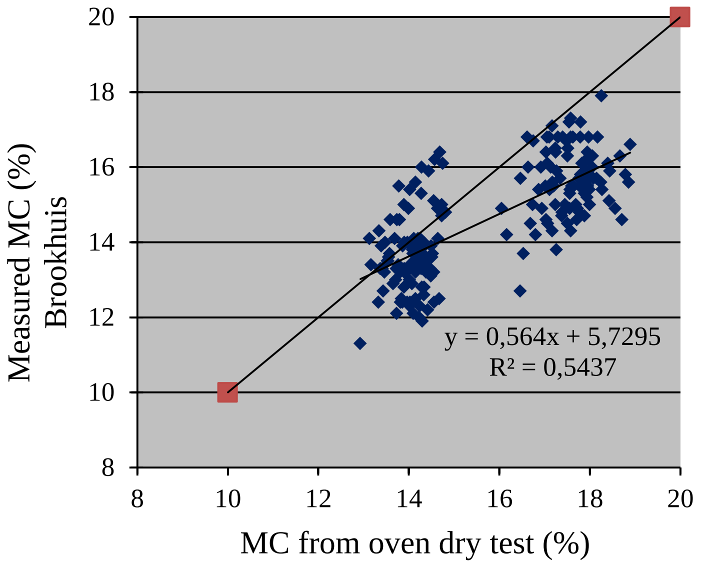


Figure 23: Relation between measured MC and MC from oven dry test.

The measurement errors for MC class 1 are presented in the histogram below, Figure 24. Wood type “fine” and “check” have a more positive error than the rest of the pieces. This is due to their higher density. A piece of wood with high density contains more water than a piece with lower density if their MC percentage is the same. This is a known limitation for capacitance moisture meters (Eliasson 1989). Brookhuis offers equipment for density compensation that can be used side by side with the moisture meter to get rid of the problem. For a production situation where the wood pieces have a homogenous density, density compensation is not needed since the equipment will be calibrated for the density level used. Despite its high systematic error, wood type “fine” have the lowest standard deviation for the measuring errors (Table 5). If the equipment was calibrated with wood type “fine”, the systematic error would decrease and a more accurate measurement would occur. As a result of the change in calibration, the pieces with low density would be measured with a negative systematic error.

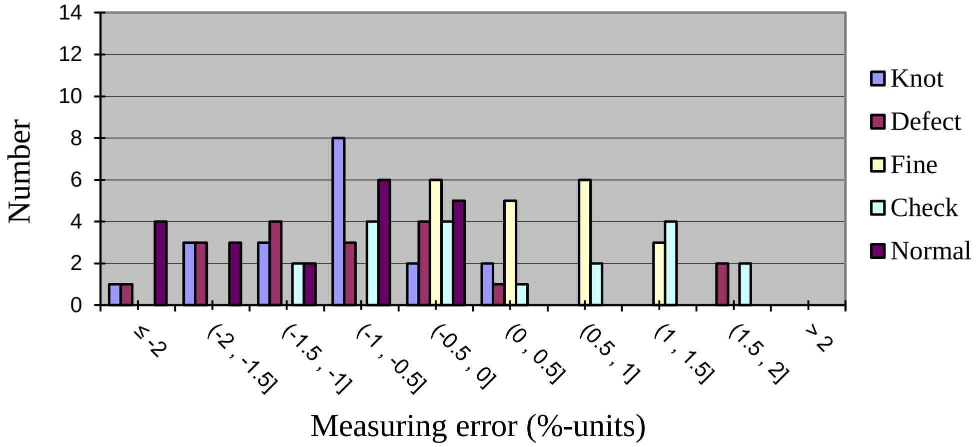


Figure 24: Histogram showing measuring error for all wood types in MC class 1(Brookhuis)

Both systematic error and standard deviation for the measuring errors are dependent on the deviation in density for the test material. A wood type class with high density generates a more positive systematic error and vice versa. A high deviation in density within a wood type class is therefore generating a high standard deviation in the measuring errors. The wood types “defect” and “check” have the highest deviation in density (Table 5) and this is probably affecting the standard deviation in systematic error since these two wood types represents the highest standard deviations in the measuring errors. If the systematic error is ignored for wood type “fine”, the measuring accuracy is ± 0.90% (90% confidence interval). This accuracy is regarded as approved according to the goal of ± 1 (90% confidence interval) that was stipulated in the main project. The measure accuracy of “normal” wood type is ± 1.28% (90% confidence interval).

Table 5: Average error, standard deviation and systematic error for MC class 1 (Brookhuis)

Knot			**Knot**	
Average error (%)	-0.92		Systematic error (%)	0.20
St.dev	0.64		St.dev	0.64
Defect			**Defect**	
Average error (%)	-0.65		Systematic error (%)	0.47
St.dev	1.06		St.dev	1.06
Fine			**Fine**	
Average error (%)	0.38	Calibration (Normal wood)	Systematic error (%)	1.50
St.dev	0.52		St.dev	0.52
Check			**Check**	
Average error (%)	0.24		Systematic error (%)	1.36
St.dev	1.04		St.dev	1.04
Normal			**Normal**	
Average error (%)	-1.12		Systematic error (%)	0.00
St.dev	0.74		St.dev	0.74

Figure 25 shows the measuring errors for MC class 2 for Brookhuis. Apart from the five wood type classes, a class with moisture gradient is included in the test. The high positive average error should not be compared with other wood types because the moisture gradient pieces have a thicker dimension than the calibration pieces and the rest of the wood type classes. All gradient staples are nicely gathered which indicates an accurate measuring of wood pieces with moisture gradient.

All wood type classes except for “gradient” have a high negative measuring error. This is probably a result from the wide calibration span that was used. A calibration span from 8% to 18% is by far too wide to get an accurate average measurement of the MC.

The trend in density and standard deviation in measuring error is the same in MC class 2 as in MC class 1. A uniform density within a wood type class generates a low standard deviation in the measuring error. The “defect” and “check” classes have the highest deviations in density and the highest standard deviation in the measuring error. Exactly the same as for MC class 1. Without further investigation it is hard to tell to what extent the actual wood type infect the measuring result since the deviation in density seems to be more crucial for the resulting measurement.

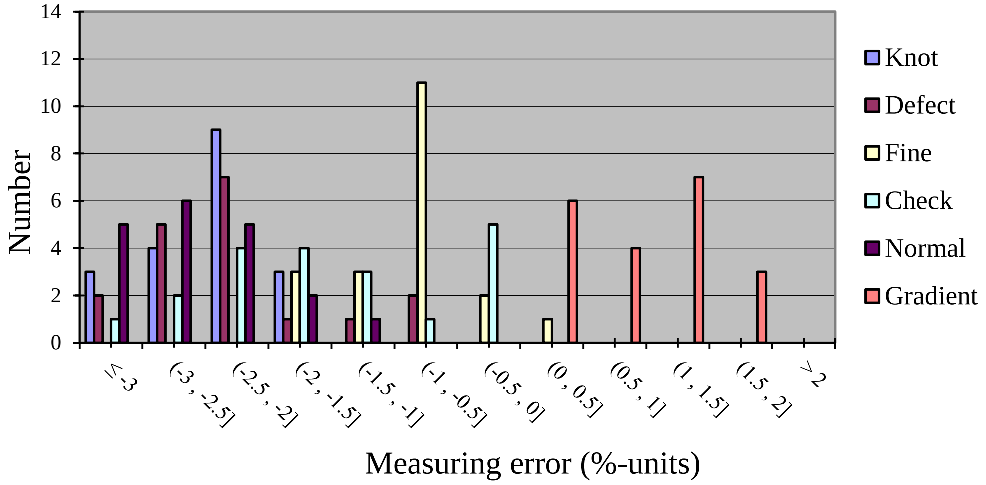


Figure 25: Histogram showing measuring error for all wood types in MC class 2(Brookhuis)

The right hand side of Table 6 shows the systematic errors for MC class 2 after a perfect calibration with a “normal” wood type. The figures confirm the importance of density compensation if the densities vary within the measured batch.

Wood type “knot”, “fine” and “gradient” are all approved according to the ± 1 (90% confidence interval) goal, if the systematic error is zero. The standard deviation in measuring error for “normal” wood type gives the measure accuracy ± 1.18% with a 90% confidence interval.

Table 6: Average error, standard deviation and systematic error for MC class 2 (Brookhuis)

Knot			**Knot**	
Average error (%)	-2.39		Systematic error (%)	0.21
St.dev	0.53		St.dev	0.53
Defect			**Defect**	
Average error (%)	-2.32		Systematic error (%)	0.29
St.dev	0.72		St.dev	0.72
Fine			**Fine**	
Average error (%)	-0.86		Systematic error (%)	1.75
St.dev	0.51		St.dev	0.51
Check		Calibration (Normal wood)	**Check**	
Average error (%)	-1.52		Systematic error (%)	1.09
St.dev	0.98		St.dev	0.98
Normal			**Normal**	
Average error (%)	-2.61		Systematic error (%)	0.00
St.dev	0.68		St.dev	0.68
Gradient			**Gradient**	
Average error (%)	0.92		Systematic error (%)	3.53
St.dev	0.51		St.dev	0.51

Figure 26 is a weight plot with the measuring error (Diff MC) as Y factor and test material parameters and measuring result as X factors. As expected, the density is highly influential to the measuring error. High density gives a positive contribution to the measuring error because all density parameters and the Y variable are located on the same side of the origin (0,0). The reference MC parameter (MC) is the most important factor and this is probably due to the calibration.

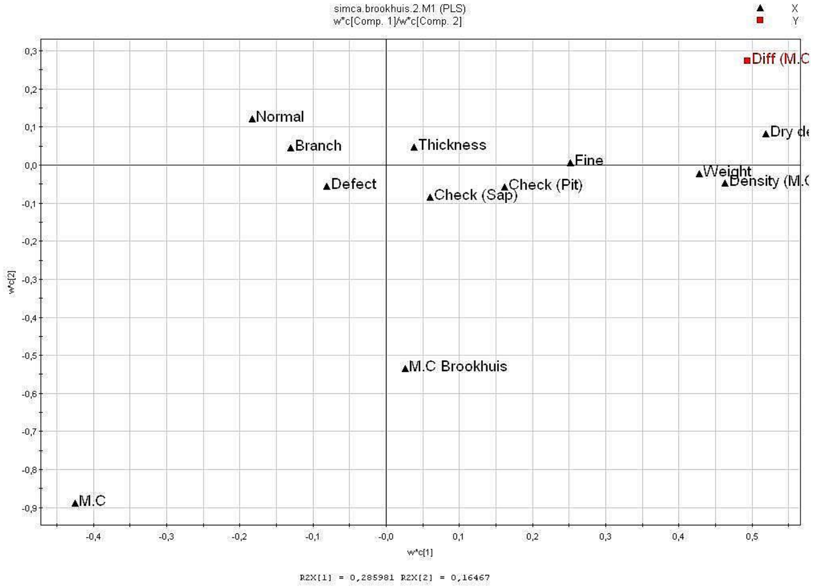


Figure 26 : Weight plot with the difference between measured value from Brookhuis and reference MC as response (Diff (M.C)).

4.3 Timberscan

The relation between measured MC from Timberscan and MC from the oven dry test is seen in Figure 27 below. The two clusters are well gathered and the R2 value is relatively high which indicates a low standard deviation in the measuring errors. The MC class 1 cluster have a positive distinct average measuring error while the MC class 2 cluster better fits the reference line.

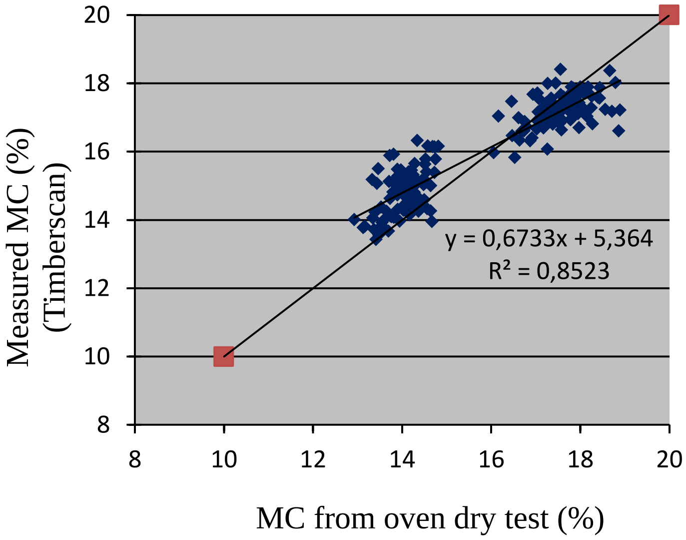


Figure 27: Relation between measured MC and MC from oven dry test (Timberscan)

The measuring errors for MC class 1 are presented in Figure 28 below. Wood type “check”, “knot” and “fine” sticks together with the calibration wood type “normal” which indicates that Timberscan is not sensitive to varying density within the measured batch. The two classes “knot” and “defect” have a more positive average error than the rest of the classes. The reason for this is probably a wave phenomenon that occurs when the electromagnetic field hits a disturbance in the measured wood within the same range of dimension as the wavelength that is used. The disturbance in this case is a knot or defect of some sort. This will be further investigated later on.

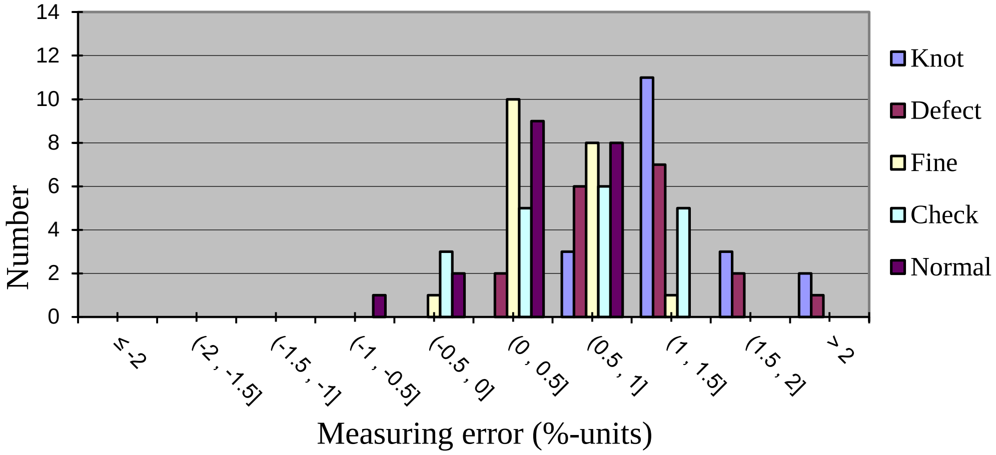


Figure 28: Histogram showing measuring errors for all wood types in MC class 1(Timberscan)

All standard deviations for the measuring errors in Table 7 are low and they would all pass the goal of ±1% with a 90% confidence interval. The measurement errors of wood type "fine" have the lowest standard deviation and the resulting accuracy is ±0.50 with a 90% confidence interval (without average and systematic error). The highest standard deviation had the wood type "defect". The resulting accuracy, calculated from the standard deviation is ±0.88% (90% confidence interval).

Table 7: Average error, standard deviation and systematic error for MC class 1 (Timberscan)

Knot			**Knot**	
Average error (%)	1.36		Systematic error (%)	1.03
St.dev	0.37		St.dev	0.37
Defect			**Defect**	
Average error (%)	1.07		Systematic error (%)	0.75
St.dev	0.53		St.dev	0.53
Fine		Calibration (Normal wood)	**Fine**	
Average error (%)	0.47		Systematic error (%)	0.15
St.dev	0.29		St.dev	0.29
Check			**Check**	
Average error (%)	0.60		Systematic error (%)	0.28
St.dev	0.51		St.dev	0.51
Normal			**Normal**	
Average error (%)	0.32		Systematic error (%)	0.00
St.dev	0.40		St.dev	0.40

Figure 29 shows the measuring errors of MC class 2 in a histogram. The distribution of measuring errors seems low, since most of the staples are nicely gathered. Wood type "defect" have an almost free-standing, five pieces high staple to the right of the other "defect" staples.

In MC class 2 the wood types “knot” and “defect” got the highest systematic error, but not to the same extent as in MC class 1. Both the systematic error and standard deviations are low for MC class 2. According to Table 7 and Table 8 Timberscan has a very good accuracy when measuring wood types with a homogenous character such as the “fine” class. Mixed densities within the measured batch is not a problem. Irregularities such as “knots” and “defects” could on the other hand be a restriction when Timberscan is used in production. It is probably fully possible to develop a signal processing algorithm to reduce the influence of knots and defects.

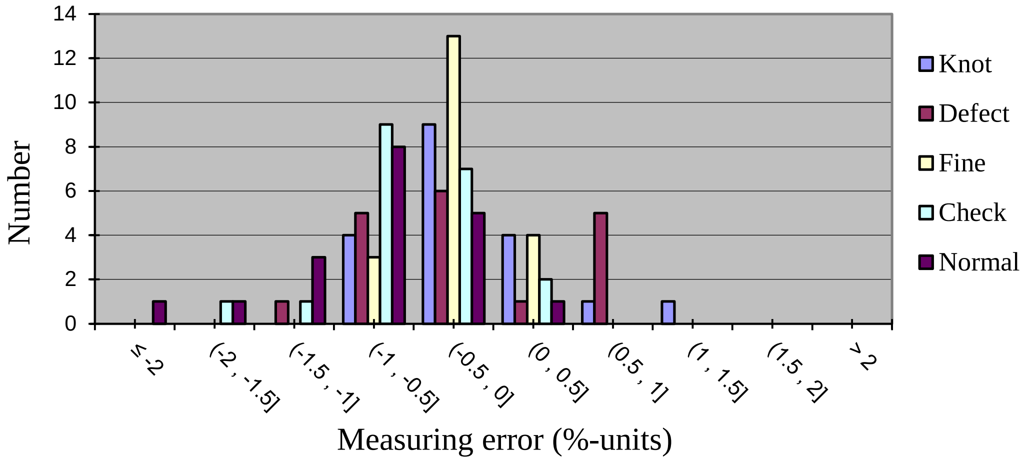


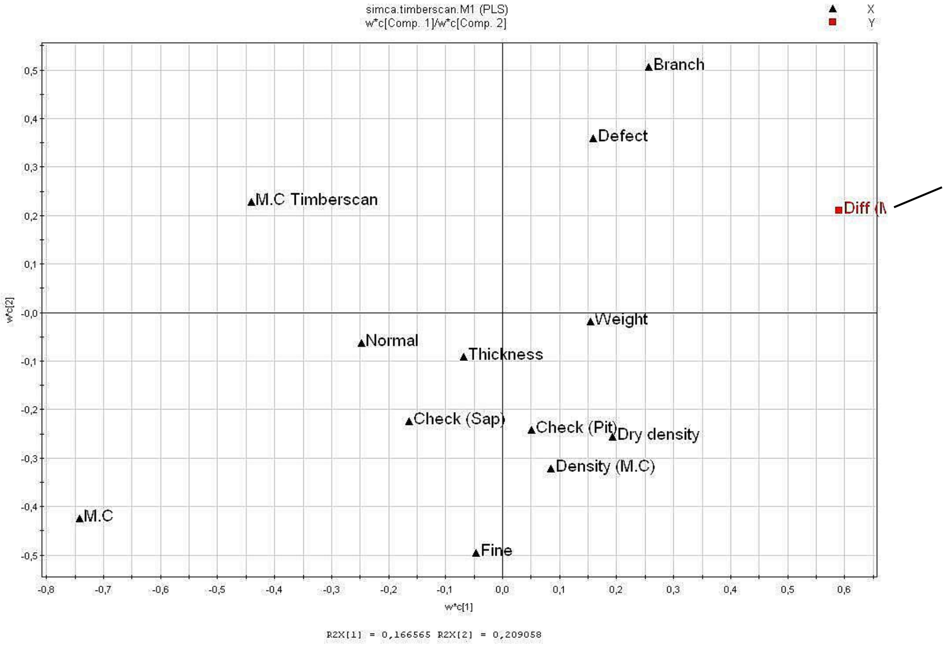
Figure 29: Histogram showing measuring errors for all wood types in MC class 2(Timberscan)

Without the systematic error, Timberscan measured the wood type “fine” with an accuracy of ±0.43% (90% confidence interval) which is the best accuracy in MC class 2. The accuracy of wood type “defect” is ±1.1% (90% confidence interval)

Table 8: Average error, standard deviation and systematic error for MC class 2 (Timberscan)

Knot			**Knot**	
Average error (%)	-0.13		Systematic error (%)	0.61
St.dev	0.48		St.dev	0.48
Defect			**Defect**	
Average error (%)	-0.14		Systematic error (%)	0.60
St.dev	0.63	Calibration (Normal wood)	St.dev	0.63
Fine			**Fine**	
Average error (%)	-0.22		Systematic error (%)	0.52
St.dev	0.25		St.dev	0.25
Check			**Check**	
Average error (%)	-0.54		Systematic error (%)	0.20
St.dev	0.47		St.dev	0.47
Normal			**Normal**	
Average error (%)	-0.74		Systematic error (%)	0.00
St.dev	0.61		St.dev	0.61

The two X factors Defect and Branch (Knot) in the weight plot (Figure 30) have a high positive influence on the measuring error, while the X factor fine have almost none influence. This is also proved by Table 7 and Table 8.The thickness of the wood pieces seems to have low or no impact since the X factor Thickness is located close to the origin.



Diff (M.C)

Figure 30: Weight plot with the difference between measured value from Timberscan and reference MC as response (Diff (M.C)).

All histograms, tables and weight plots tell that Timberscan generates too high MC values when measuring wood with distinct knots. According to Table 7, the systematic error for the knot group in MC class 1 is 1.03% for example.

The following figure show the logged values for Timberscan during the measuring of a wood piece in the “knot” group, Figure 31. The blue line is the Timberscan values and the red dotted line is the reference MC from oven dry method. Note that the oven dry test was carried out at one end of the plank and the oven dry MC was then assumed to be homogenous along the plank, due to the long conditioning. At approximately 40 cm into the plank there are two distinct fresh knots located. One can see that these knots give rise to two peaks in the measured MC. These two peaks have a great impact on the measured MC since the measured MC often is an average or median (median is used in this investigation) value of the total number of measurements along the board or plank. The two peaks are probably a diffraction pattern caused by one or both knots. The knots contain of a denser matter which may give rise to a diffraction phenomenon. An indication that this is the case is that the distance between the two peaks is 11-12 cm (Figure 31), which is the same as half of the wavelength at the frequency used in Timberscan (11.5cm). This needs to be further investigated and affirmed. To avoid this source of error signal filtering needs to be developed. A wavelength in the same order of magnitude as the defects or knots (microwave span) seems otherwise to be a problem when measuring MC inline. The measured MC value is close to the reference MC value when measuring in clean wood.

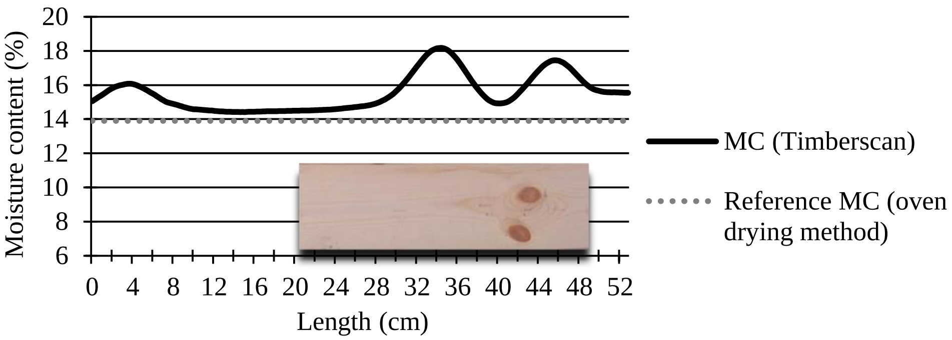


Figure 31: Measured MC along a plank with fresh knots (Timberscan). A part of the measured piece of wood is shown in the figure.

The results of a repeatability test are seen in Table 9. The highest deviation in MC is three hundredths of a per cent (piece nr 2 and 5). The results show that Timberscan generates nearly identical values on MC if a piece is measured several times.

Table 9: *Repeatability of five test pieces.*

Piece Nr 1	
Test 1	16.19
2	16.2
3	16.19
Piece Nr 2	
Test 1	14.86
2	14.86
3	14.83
Piece Nr 3	
Test 1	14.85
2	14.85
3	14.85
Piece Nr 4	
Test 1	15.12
2	15.13
3	15.12
Piece Nr 5	
Test 1	15.98
2	15.96
3	15.95

5. Conclusions

5.1 Accuracy

One of the objectives in the main project was to find or develop equipment measuring MC in wood with an accuracy of ±1% (90% confidence interval) within the interval 7-18% MC. This accuracy or objective is to some extent fulfilled when looking at the measuring errors.

- MiCROTEC M3SCAN shows good accuracy when measuring wood type “knot” and “normal” in both MC classes. In MC class 2, wood type “fine” is also good. No connection between high density and measuring error has been found in the results. The errors and deviation in errors is probably more connected to the amount of extractives. Unfortunately, the amount of extractives in test material was not taken into account which makes it hard to see the relationship

- The Brookhuis equipment is sensitive to variations in density. This can be seen in the results of this test. This equipment is well suited in production were the density is relatively homogenous. The alternatives are to calibrate for density classes, which is not realistic in industry or to implement a density compensator

- Timberscan shows very good accuracy for high quality wood, such as wood type “fine”. When measuring wood with big knots, the measured value is too high. The Timberscan equipment is suitable for carpentry industry for example where good quality wood already has been sorted out

Obstacles:

- The calibration span used (8% to 17.5% MC) was too wide to get an accurate measurement. This conclusion concerns all three moisture meters. If a more narrow calibration span had been used, the measuring errors would probably be smaller
- There are big differences in systematic measuring errors between the wood type groups. Therefore it becomes important to minimize differences in the wood features within a measured batch. To attain good accuracy, the equipment needs to be calibrated with the wood features in mind. On the other hand, in industry wood with different features and varying MC will pass the equipment. Therefore it will be necessary to improve or complement the moisture measuring equipment so it will be able to identify the wood features and for example by filtering techniques distinguish between moisture and wood tissue during the measurement

According to the measuring results, there are several differences between the investigated equipment. Since there was no information on how the MiCROTEC and Brookhuis equipment worked (frequency etcetera) due to industrial secrets, it is somehow hard to connect the measuring result to measuring method.

6. Future work

During this thesis, several questions and possible side tracks were found. Since this kind of work is time limited it was not possible to investigate them. The future work is preferably carried out side by side with an equipment supplier. Following questions would be interesting to look closer into:

- How the amount and type of extractives are affecting the dielectric properties of wood. In softwood, the amount of extractives varies between species, individuals, sapwood and heartwood for example. This might explain some of the deviatios in measuring errors. An investigation on the reactions of identified extractives exposed to electromagnetic fields at varying wavelength would be interesting
- The possibility to filter the signals from the inline MC meters to increase the accuracy. When using microwaves (1.3 GHz) to predict the MC, it was found that knots probably cause diffractions which result in a high positive measuring error. By the use of signal filtering, this source of error could be reduced
- Investigate, develop and apply standards for calibration. Some sawmills have invested in inline MC meters, but due to low accuracy they are not used. One of the reasons is insufficient calibrations. An investigation should include a levelling study to find out to what extent it is profitable to improve the calibration. A well-made calibration is crucial to attain accurate measurements, but the process is time consuming and demand good machine operators

It is also important to continuously inform the sawmill industry about the benefits of assuring the quality of their delivered goods. By assuring the quality by the use of inline MC meters, a win - win situation will occur. Competitive edge will arise for sawmills if they can assure the quality and at the same time, the over drying can be reduced (Figure 1). To strengthen wood as an engineering material the benefits in investing in better measuring equipment need to be spread.

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