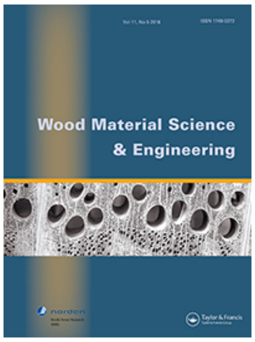

Wood Material Science & Engineering

ISSN: 1748-0272 (Print) 1748-0280 (Online) Journal homepage: http://www.tandfonline.com/loi/swoo20

Moisture content measurements in wood using dual-energy CT scanning – a feasibility study

Owe Lindgren, Thomas Seifert & Anton Du Plessis

WOOD MATERIAL SCIENCE & ENGINEERING, 2016
VOL. 11, NO. 5, 312–317
http://dx.doi.org/10.1080/17480272.2016.1201863

Taylor & Francis
Taylor & Francis Group

Moisture content measurements in wood using dual-energy CT scanning – a feasibility study

Owe Lindgren[a], Thomas Seifert[b,c] and Anton Du Plessis[b,c]

[a]Wood Science and Engineering, Luleå University of Technology, Skellefteå, Sweden; [b]Department of Forest & Wood Science, Stellenbosch University, Stellenbosch, South Africa; [c]Central Analytical Facilities, Stellenbosch University, Stellenbosch, South Africa

ABSTRACT

Currently computed tomography (CT) scanning provides a non-destructive method to determine moisture content in wood in three dimensions. With the current methodology two measurements are needed, one with the scanned piece of wood's moist state and one after drying. Then the difference of the images can be calculated. The drawback and challenge is that dimensional changes due to shrinkage of wood in the drying process have to be compensated for by image processing. In this study a dual-energy CT scanning method is tested based on the consecutive scanning of wood samples at different energy levels to differentiate water from wood, without the necessity to dry the sample and thus without the need for complex image correction. Not quantified but visible differentiations due to moisture content were obtained on small cubical pine samples of different densities by quick consecutives scans at 60 and 200 kV. The results suggest that given that the pixels in the CT images are representing absorption coefficients it should be possible to directly measure moisture content in wood non-destructively in small volume elements inside solid wood in three dimensions. Further applications of this technique in industrial CT scanning of wood are discussed.

ARTICLE HISTORY
Received 7 January 2016
Revised 12 June 2016
Accepted 12 June 2016

KEYWORDS
CT scanning; X-ray; computed tomography; dual energy; wood moisture determination; non-destructive testing

1. Introduction

Moisture content is known to influence major wood properties such as mechanical strength (Kollmann 1936, pp. 162, 180, 189), natural durability (Taylor *et al.* 2002, Sandberg 2008) as well as wood conversion processes' drying behaviour (Danvind and Synnergren 2001). Accurate and efficient wood moisture determination is thus an important task in wood research and a prerequisite for efficient wood processing.

Sometimes it is desirable to measure moisture content non-destructively and determine the moisture distribution in the sample three dimensionally. For that reason imaging methods based on tomography have been introduced. The most frequently applied tomography methods for wood and timber samples are based on magnetic resonance imaging (Bucur 2003, Dvinskikh *et al.* 2011) and X-ray-based tomography, also named Computerized axial tomography or CT scanning (Lindgren 1992, Fromm *et al.* 2001). Of both these technologies X-ray-based CT scanning is the technology that is introduced more widely due to its wide range of applications on dry and wet wood (e.g. zu Castell *et al.* 2005, Seifert *et al.* 2010, Wei *et al.* 2011).

A robust, accurate, and at the same time fast measurement of wood moisture content grants a lot of benefits for scientific studies of moisture movement in the kiln drying process (Wiberg and Morén 1999), in natural durability studies (Sandberg and Salin 2012) and for eco-physiological research (Nikolova *et al.* 2009). It also paves the way for further optimisation in the timber production process with regards to optimised sawing, kiln drying, and chemical and thermal treatment.

The measurement of moisture content using X-rays is based on the attenuation coefficient, or in other words the proportion of X-ray photons that are absorbed by the material per unit length of the sample. The absorption follows the Lambert-Beers law as outlined by Lindgren (1992) (Equation 1).

$$I = I_0 e^{-\mu t} \tag{1}$$

where I is the intensity of the transmitted X-ray beam, I_0 is the intensity of the incident X-ray beam, μ is the linear attenuation coefficient and t is the thickness of the samples that is penetrated by the X-ray beam.

The attenuation coefficient in turn is determined by a compound of the moisture content, the wood density and atomic numbers and thus by the chemical wood composition. Since wood gross chemical composition can be assumed to be rather constant the problem can be reduced to wood–water relations. A challenge in the application of this technique of moisture determination based on CT scanning is that samples have to be scanned twice; once fresh and then again after oven-drying, which always left the inherent problem of shrinkage correction (Lindgren 1992, Nikolova *et al.* 2009).

We propose a dual-energy scanning method for industrial micro CT scanners in this article, which is based on two scans in short succession at wet samples that are conducted at

CONTACT Owe Lindgren owe.lindgren@ltu.se

Table 1. Calculation of volume % of water content in wood.

Vol. dm^3	Dry density kg/m^3	Mass wood kg	Vol. wood kg	m.c.	Mass H_2O kg	Vol. H_2O dm^3	Total vol. dm^3	Vol% wood	Vol% H_2O	Total density kg/m^3
300	500	150	100	0	0	0	300	0.33	0.00	500.00
300	500	150	100	0.1	15	15	315	0.32	0.05	523.81
300	500	150	100	0.2	30	30	330	0.30	0.09	545.45
300	500	150	100	0.3	45	45	345	0.29	0.13	565.22
300	500	150	100	0.5	75	75	345	0.29	0.22	652.17
300	500	150	100	0.7	105	105	345	0.29	0.30	739.13
300	500	150	100	0.9	135	135	345	0.29	0.39	826.09
300	500	150	100	1.1	165	165	345	0.29	0.48	913.04

Note: m.c., moisture content.

different acceleration voltages (energy levels). The method has been successfully demonstrated for material differentiation in medical sciences (Kalender 2011) and first tests of dual-energy X-ray absorptiometry on wood have shown the feasibility of the dual-energy concept to determine wood moisture content (Kullenberg *et al*. 2010, Tanaka and Kawai 2013, Kim *et al*. 2015). However, these studies were limited to two-dimensional X-ray scans that do not allow a tomographic reconstruction of wood moisture content in three dimensions.

In this article, an extension of these absorptiometry-based dual-energy approaches is presented based on data obtained from an industrial CT scanner. The novel methodology to measure moisture content in wood three dimensionally is meant to overcome the traditional problem of moisture shrinkage correction by using the differentiation of different atomic numbers of wood and water when CT scans are conducted at different acceleration energies. Thus a true differentiation between water and density effect on X-ray absorption is expected.

The linear X-ray attenuation coefficient of wood is calculated according to Tsai and Cho (1976) with the challenge with regards to attenuation calculations posed by the fact that water can be absorbed or desorbed into and out of wood. This complicates calculations since the attenuation coefficient is dependent on volume percentage of wood and volume percentage of water instead of a weight-based percentage as is generally used in wood science. Wood density can be calculated according to Equation 2:

$$\rho_{\text{tot}} = \omega_{\text{wood}}\rho_{\text{wood}} + \omega_{\text{water}}\rho_{\text{water}} \tag{2}$$

where ρ_{tot} is the total density, w_{wood} is the volume percentage wood, ρ_{wood} is the compact density of wood (approx. 1500 kg/m^3), w_{water} is the volume percentage water and ρ_{water} is the density of water.

However, there is an analogy with calculating wood density and the linear attenuation coefficient of wood including different moisture content levels as illustrated in the following example:

Assume a piece of wood shows a dry density of 500 kg/m^3 at a volume of 300 dm^3. Also assume the compact density of wood is 1500 kg/m^3.

Now we assume 10% moisture content is added to the wood. Then the mass of wood is still 150 kg. 10% moisture corresponds to 15 kg. The total volume has however increased to 315 dm^3. The wood cells have absorbed all the 15 kg water, as it is hygroscopic.

At the fibre saturation point (FSP) the cell walls are saturated with water. In general it can be said that FSP is reached at around 30% moisture content. Above FSP no more water can be added to the cell walls and if further water is to be absorbed all water is found in the cell lumina as “free water”.

Table 1 illustrates the changes in total density and volume % of wood and water.

Based on the relation of moisture content from Table 1, Figure 1 illustrates how moisture content changes the density of wood using volume % according to Equation 2 which is the general material blending rule. In this case dry wood density is 500 kg/m^3.

The reason for the difference in slope below 30% and above 30% is that wood stops swelling at FSP.

In accordance with this the relationships between X-ray attenuation coefficients and wood density and moisture content show the same behaviour. This occurs even though the attenuation coefficients of water below or above 30% and wood are identical. A detailed explanation can be found in Lindgren (1992).

The reason for using volume % above is simply that X-ray absorption coefficient is calculated using volume % of wood and moisture content in analogy to Equation 3.

$$\mu_{\text{tot}} = w_{\text{wood}}\mu_{\text{wood}} + w_{\text{water}}\mu_{\text{water}} \tag{3}$$

where μ_{tot} is the total linear attenuation coefficient, w_{wood} is the volume percentage wood, μ_{wood} is the linear attenuation coefficient at a wood density of approximately 1500 kg/m^3, w_{water} is the volume percentage water and μ_{water} is the linear attenuation coefficient of water at a density of 1000 kg/m^3.

Using the equations by Tsai and Cho (1976) the linear attenuation coefficient can thus be calculated accordingly.

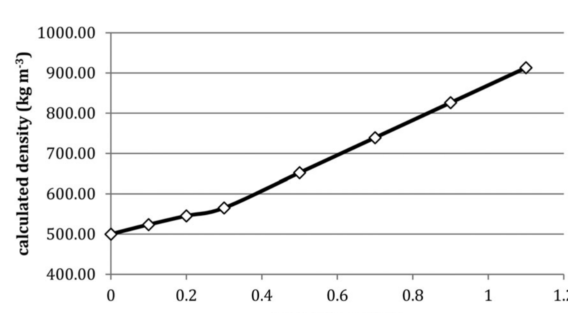

Figure 1. Calculated density increase of wood at increasing moisture content levels if volume % is used as a reference in calculation.

2. Materials and methods

A commercial micro CT system, the General Electric Phoenix V|Tome|X L240 / NF180, was used in this study. This system allows a wide range of sample sizes to be scanned at significantly different conditions, most important of which in this study are the voltage variation capabilities. X-ray settings were set to 200 kV and 60 kV in sequential scans of the same object, at identical resolution. These kV levels were chosen to be comparable to the keV levels used in calculations below. For this the current must be limited to ensure a similar X-ray spot size, which could otherwise limit the resolution of the system at high voltage and current combinations. In this study it was particularly important to do fast scans to ensure minimal drying and water movement during and between the scans. For this purpose settings of reduced resolution (100 µm) and reduced number of projection images (800) were applied, resulting in approximately 4 min per scan, while typical scan time is 30–60 min. That resulted in an acquisition time per projection of 250 ms.

A simple test was performed. The high-resolution CT scanner in Stellenbosch has a high variability of energy levels that can be preselected for scanning. Four cubical wood pieces of Scots pine sapwood (*Pinus sylvestris* L.), 30 mm × 30 mm in cross-section, were cut and saturated with water (moisture content exceeding 100%). They were all scanned simultaneously in the scanner simply by stacking them on top of each other. Reconstruction was done with system-supplied Datos reconstruction software, based on a modified Feldkamp algorithm (Feldkamp *et al.* 1984). Image analysis was performed with Volume Graphics VGStudio Max 2.1 and ImageJ (2010).

3. Results and discussion

3.1. Theoretical base for dual X-ray energy calculations for moisture content measurements

As stipulated before, the attenuation coefficient changes depending on difference not only in density, but also in effective atomic number and X-ray energies. Figure 2 shows how the relationship between linear attenuation coefficient and moisture content changes depending on only change in X-ray energy. In this case 40 and 150 keV were used in the calculations and a wood density of 500 kg/m^3 at different moisture content levels.

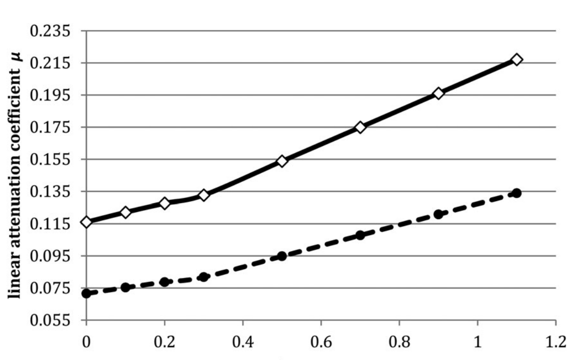

Figure 2. Increase of linear attenuation coefficient of wood with increasing moisture content levels at X-ray energies of 40 and 150 keV.

It is clear that the slope is lower at 150 keV (below) than at 40 keV (top). However, this also goes for the slope depending on dry wood density. These differences in slope raise the expectation that a change in X-ray energy could result in being able to separate moisture content in wood from the total wood density.

Kullenberg *et al.* (2010) and Kim *et al.* (2015) have investigated this and tests showed promising results. According to X-ray physics, the process using CT scanning instead of using the radiography method they used would require to divide the pixel values in two CT images taken at two different X-ray energy levels. This is naturally under the assumption that the two CT images are matrices showing the attenuation coefficient in each pixel. This assumption is not trivial since this is, that is, not the case using medical CT scanning where the images contain matrices of CT numbers that are normalised attenuation values to the value of water. The resulting constant can then be correlated to moisture content accordingly.

The relations stipulated in Equations 4 and 5 are valid as representations of Equation 1 as also stipulated by Kullenberg *et al.* (2010) and Kim *et al.* (2015):

$$N_1 = N_{0,1}e^{(-\mu_1 X)} \quad (4)$$

$$N_2 = N_{0,2}e^{(-\mu_2 X)} \quad (5)$$

where N_i is the observed transmitted count rate for energy *I*, $N_{0,i}$ is the count rate for energy *I* with no attenuator, μ_1, μ_2 are the linear attenuation coefficients for energy *I* and *X* is the thickness of the sample.

Equations 4 and 5 can also be rewritten into Equations 6 and 7:

$$\ln\left(\frac{N_{0,1}}{N_1}\right) = \mu_1 X \quad (6)$$

$$\ln\left(\frac{N_{0,2}}{N_2}\right) = \mu_2 X \quad (7)$$

The count rates without attenuator could be determined besides the object or attenuator. From Equations 6 and 7 an expression called *k* can be derived by dividing the two equations (Equation 8):

$$k = \left(\frac{\ln(N_{0,1}/N_1)}{\ln(N_{0,2}/N_2)}\right) = \frac{\mu_1 X}{\mu_2 X} = \frac{\mu_1}{\mu_2} \quad (8)$$

The expression in Equation 8 is only dependent of the linear attenuation coefficient, which in its turn is only dependent on the change of moisture content.

Table 2 shows the results of the calculated *k*-values, and it can be found that the constant is the same independent of wood density and decreases with increasing moisture content level. Here the X-ray energies of 40 and 150 keV were used as an example.

This can also be seen in Figure 3.

Therefore a straight forward solution might be to CT scan the sample first at a low X-ray energy and secondly to CT scan the sample at a high X-ray energy. If then the images

Table 2. Constant *k*-value at different wood densities but *k*-values decrease with increasing moisture content level.

MC	k 500 kg m^{-3}	k 450 kg m^{-3}	k 400 kg m^{-3}
0	1.622263624	1.622263624	1.622263624
0.1	1.622254079	1.622254079	1.622254079
0.2	1.622246187	1.622246187	1.622246187
0.3	1.622239552	1.622239552	1.622239552
0.5	1.622229017	1.622229017	1.622229017
0.7	1.622221027	1.622221027	1.622221027
0.9	1.622214760	1.622214760	1.622214760
1.1	1.622209713	1.622209713	1.622209713

Note: MC, moisture content.

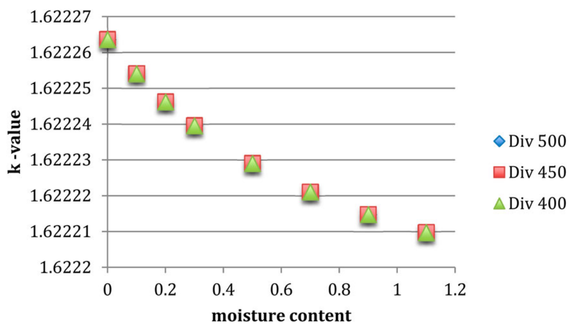

Figure 3. The *k*-value stays constant at different wood densities, ranging from 400 to 600 kg/m^3, but decreases with increasing moisture content levels.

are exported into an image-processing program the two images can be divided with each other, which should result in a representation of *k*. The *k*-value in its turn is a function of moisture content. This is a much simpler procedure than the one used by Lindgren (1992).

The differences in *k*-value above are small and during scientific calibration this might result in not so excellent accuracies. However, there is always the possibility to make identical CT scans and digitally average them, resulting in a decrease of noise for each addition Lindgren (1992).

3.2. Results of the analysis of the scans

CT images of the dual-energy scans after image processing using ImageJ developed by National Institutes of Health in the USA are shown (Figure 4). To the left, the CT image at 200 kV, in the middle the CT image at 60 kV and to the right the result after dividing the image at 200 kV with the image at 60 kV.

The image furthest to the right should be a representation of a 2-D moisture content distribution according to Equations 2–8. However, a full calibration has not yet been performed. By stacking images to reduce noise in the image-processing program a 3-D representation of moisture content is possible (Figure 5). Higher levels of moisture content are represented as yellow, a middle level as whiter grey scale, and lower levels as a darker grey scale.

With this study we were able to show that using dual-energy CT scanning for moisture content determination might be possible. This novel application is extending the dual-energy scanning on the CT scans concept to wood, which has so far only been tested in X-ray absorptiometry studies (Kullenberg *et al.* 2010, Tanaka and Kawai 2013, Kim *et al.* 2015) that were limited to two-dimensional applications. The application of two quick consecutive scans for moisture determination represents a major step ahead from existing methods (Lindgren 1992, Nikolova *et al.* 2009) since the drying step in between the two scans can be omitted and no image analysis-based correction of the wood shrinkage during drying is necessary.

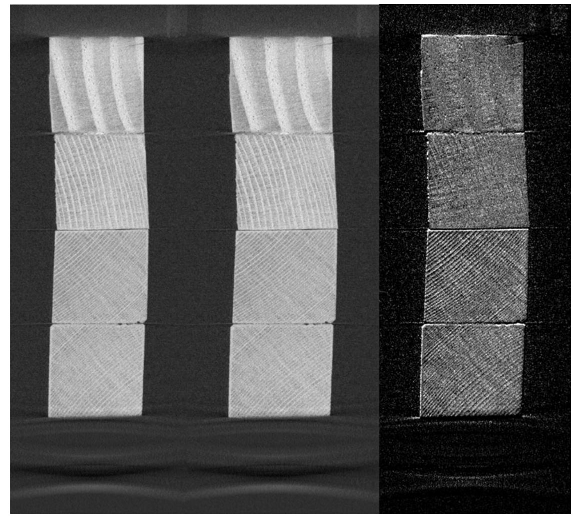

Figure 4. To the left the CT image at 200 kV, in the middle the CT image at 60 kV and furthest to the right the result after dividing the image at 200 kV with the image at 60 kV.

Clearly a dry shell was found in our samples as described by Wiberg and Morén (1999) close to the wooden surfaces. An interesting observation was that the water content was

Figure 5. Three-dimensional visualisation of the moisture distribution in the divided image.

higher in the late wood, as the grey scale of the annual growth rings are whiter than that of early wood after image division in Figure 4.

We argue that the use of the linear attenuation coefficient has advantages over the use of the mass attenuation coefficient as proposed by Tanaka and Kawai (2013) and Kim *et al*. (2015) in a dual-energy absorptiometry study. Using mass attenuation values is problematic as linear attenuations are based on volume percentages as shown before.

This study was conducted on an industrial micro CT scanner with a wide range of available energy levels. This was a prerequisite because traditional medical CT scanners provide only two energy levels, typically ranging from 60 to 80 keV, which are set for optimal medical scanning of the human body within medically acceptable radiation parameters. The energy difference might be too small to achieve similar results than in this study, where 60 and 200 kV were used.

It must be mentioned that calibrations depend on type of X-ray source and the energy levels chosen. An optimisation of the energy levels should thus follow in future studies as well as the application of different filters at the different energy levels, which has been reported to reduce the noise in dual-energy scans significantly (Marshall *et al*. 1984).

The resulting images are to a large degree representations of the attenuation coefficient but also an influence of the material can be expected (Lindgren 1992, Kalender 2011). There will most likely be differences in calibration curves depending on the wood species. Thus further tests on different species will be necessary.

This novel application of the dual-energy application in the CT scanners technique opens up new avenues for the application of dual X-ray scanners based in the production process. With two consecutive tubes, working at different energy levels in a production line, a continuous measurement at full production speed should be possible. Spatial resolution will be lower than that used in this investigation, and thereby sampling and measurement speed will increase. The measurements should be made directly after sawing and wood is still wet to determine the incoming moisture content level before wood is dried in the kiln. A detailed and accurate information on wood moisture content would increase drying speed and most of all increase quality of drying and thus reduce losses that are currently experienced in the wood-drying process.

4. Conclusions

- Not quantified but visible differentiations due to moisture content were obtained on small cubical pine samples of different densities by quick consecutives scans (4 min each) at 60 kV and 200 kV.
- The division of the larger by the smaller energy image resulted in sufficient contrast to image the water contained in the wood in three dimensions.
- During the publication process, an investigation was conducted using a medical CT scanner which preliminarily shows accuracies of ±1.5% in moisture content measurements in a 3 mm × 3 mm × 5 mm Scots pine. This is going to be published later in 2016.
- These promising results pave the way for further future investigations and calibrations that might lead to the application of dual-energy scanning for various applications in sawing and drying operations.

Acknowledgements

This study was financed by funds made available through the rated researcher funding stream of the National Research Foundation (NRF) of South Africa in conjunction with complementary funding from Stellenbosch University. The CT scanner was funded through an NEP/RISP grant of NRF/DST. We would like to acknowledge also the Luleå University of Technology, Wood Science and Engineering, Sweden, for funding the travel of professor Lindgren.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Bucur, V. (2003) *Nondestructive Characterization and Imaging of Wood*. Springer Series in Wood Science (Berlin: Springer-Verlag, pp. 354).

Danvind, J. and Synnergren, P. (2001) Method for measuring shrinkage behaviour of drying wood using Digital Speckle Photography and X-ray Computerized Tomography. In: Proceedings of 7th International IRO Wood–drying Conference. July 9–13, Tsukuba, Japan pp. 276–281.

Dvinskikh, S.V., Furó, I., Sandberg, D. and Södertröm, O. (2011) Moisture content profiles and uptake kinetics in wood cladding materials evaluated by a portable nuclear magnetic resonance spectrometer. *Wood Material Science and Engineering*, 6 (3), 119–127.

Feldkamp, L.A., Davis, L.C. and Kress, J.K. (1984) Practical cone-beam algorithm. *Journal of the Optical Society of America A*, 1 (6), 612–619.

Fromm, J.H., Sautter, I., Matthies, D., Kremer, J., Schumacher, P. and Ganter, C. (2001) Xylem water content and wood density in spruce and oak trees detected by high-resolution computed tomography. *Plant Physiology*, 127 (2), 416–425.

ImageJ (2010) Accessed 12 November 2015 2015, available at: http://rsbweb.nih.gov/ij/download.html.

Kalender, W. (2011) *Computed Tomography: Fundamentals, System Technology, Image Quality, Applications* (Erlangen: Publicis Publishing, 330 pp).

Kim, C.-K., Oh, J.-K., Hong, J.-P. and Lee, J.-J. (2015) Dual-energy X-ray absorptiometry with digital radiograph for evaluating moisture content of green wood. *Wood Science and Technology*, 49, 713–723.

Kollmann, F. (1936) *Technologie des Holzes* (Berlin: Springer, 764 pp).

Kullenberg, R., Hultnäs, M., Fernandez, V., Nylinder, M., Toft, S. and Danielsson, F. (2010) Dual-energy X-ray absorptiometry analysis for the determination of moisture content in biomass. *Journal of Biobased Materials and Bioenergy*, 4, 363–366.

Lindgren, O. (1992) Medical CT-Scanners for Non-Destructive Wood Density and Moisture Content Measurements. Doctoral thesis 1992:111D (Luleå: Luleå University of Technology).

Marshall, W., Hall, E., Doost-Hoseini, A., Alvarez, R., Macovski, A. and Cassel, D. (1984) An implementation of dual energy CT scanning. *Journal of Computer Assisted Tomography*, 8 (4), 745–749.

Nikolova, P., Blaschke, H., Matyssek, R., Pretzsch, H. and Seifert, T. (2009) Combined application of computer tomography and light microscopy for analysis of conductive xylem area in coarse roots of European beech and Norway spruce. *European Journal of Forest Research*, 128 (2), 145–153.

Sandberg, K. (2008) Degradation of Norway spruce (*Picea abies*) heartwood and sapwood during 5.5 years' above-ground exposure. *Wood Material Science and Engineering*, 3, 83–93.

Sandberg, K. and Salin, J.-G. (2012) Liquid water absorption in dried Norway spruce timber measured with CT scanning and viewed as a percolation process. *Wood Science and Technology*, 46, 207–219.

Seifert, T., Nickel, M. and Pretzsch, H. (2010) Analysing the long-term effects of artificial pruning of wild cherry by computer tomography. *Trees*, 24 (5), 797–808.

Tanaka, T. and Kawai, Y. (2013) A new method for nondestructive evaluation of solid wood moisture content based on dual-energy X-ray absorptiometry. *Wood Science and Technology*, 47, 1213–1229.

Taylor, A.M., Gartner, B.L. and Morrell, J.J. (2002) Heartwood formation and natural durability: A review. *Wood and Fiber Science*, 34, 587–611.

Tsai, C.M. and Cho, Z.H. (1976) Physics of contrast mechanism and averaging effect of linear attenuation coefficients in a computerized transverse axial tomography (CTAT) transmission scanner. *Physics in Medicine and Biology*, 21, 544–559.

Wei, Q., Leblon, B. and La Rocque, A. (2011) On the use of X-ray computed tomography for determining wood properties: A review. *Canadian Journal of Forest Research*, 41, 2120–2140.

Wiberg, P. and Morén, T. (1999) Moisture flux determination in wood during drying above fibre saturation point using CT-scanning and digital image processing. *Holz als Roh- und Werkstoff*, 57 (2), 137–144.

zu Castell, W., Schrödl, S. and Seifert, T. (2005) Volume Interpolation of CT Images from Tree Trunks. *Plant Biology*, 7, 737–744.