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## Nondestructive determination of spruce lumber wood density using drilling resistance (Resistograph) method

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**Abstract:** The use of Resistograph for the purpose of nondestructive evaluation of certain properties of standing trees and wooden materials has increased in recent years. The resistance to penetration of a fine drill bit is measured and recorded by the device. A number of properties of the wood can be assessed by the amplitude values obtained from the Resistograph. The aim of this study was to assess the utility of the IML-Resistograph F 500 as a nondestructive tool for estimating spruce wood density using the amplitude data generated and the application of statistical modeling. Wood density data were determined using a volumetric method and were compared with the density data generated by the model. In this model, amplitude was used as an independent variable and the dependent variable for experimental purposes was wood density. No statistical difference ( $P = 0.176 > 0.05$ ; 95% confidence level) was found between the groups. Moisture content was added as second independent variable and a second model was built. The results demonstrated that wood density can be estimated nondestructively using Resistograph data from lumber and/or large wooden materials, but more comprehensive models are required for the practical use of the device in the forest products industry.

**Key words:** Modeling, nondestructive evaluation, Resistograph, wood density

### 1. Introduction

By definition, nondestructive evaluation (NDE) is a process of assessing physical and mechanical properties and developing knowledge of potential intrinsic defects of a material or its structure, without altering the end use capabilities (Ross and Pellerin, 1991; Zombori, 2001; Bucur, 2003). In recent years, major advances in NDE technologies based on portable devices have been successfully developed for wood and wood composites, offering excellent opportunities for characterization of wood in the forest products industry. In addition, standards that include nondestructive testing techniques for different materials are being implemented in many countries. Thus, NDE provides opportunities for the forest products industry at all levels to estimate product quality and to increase customer satisfaction.

Drilling resistance methods have been increasingly used in the field to characterize wood properties. The technique involves a quasidestructive mechanical drill system that measures the drilling torque of the material as a slender rotating drill bit is driven into the wood at a constant speed. The machines produce charts showing the relative resistance profile for each drill path. Because the method can reveal relative density changes along the drill path, the technique is also used to diagnose the internal

condition and to detect defects within structural lumbars and standing trees.

The Resistograph was patented in 1990 (Rinntech, Heidelberg, Germany; [www.rinntech.com](http://www.rinntech.com)), and it measures the drilling resistance of material depending on power consumption during drilling (Rinn, 1994; Rinn et al., 1996). The device consists of a power unit, a small-diameter drill bit, a paper or digital chart recorder, and an electronic device that can be connected to the serial interface input of any standard PC. The diameter of the drill bit is typically 1.5 mm, with a tip of 3 mm, so that any weakening effect of the drill hole on the wood cross-section is negligible (Dunster, 2000; Brashaw et al., 2005; Wacker et al., 2008). Advanced models have some optional features such as Bluetooth data transfer, automatic rot identification, and annual ring measurement modules (Güller et al., 2011).

Although the Resistograph was developed for the nondestructive inspection of lumber and poles, it has also been tested for the evaluation of different properties of both standing trees and sawn lumber (Kappel and Mattheck, 2003; Güller, 2005; Güller et al., 2011).

Wood density is an important quality trait and generally has a good correlation with wood strength. Inexpensive, reliable, and rapid methods for assessing this

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trait are very important in the preassessment of strength of sawn lumber in the forest product industry.

The Resistograph provides a graphic representation (a resistogram) of the energy consumed by the electric motor in penetrating a sample. Thus, given the internal constitution of the wood, a series of variables related to the characteristics of the material can be determined. The total energy consumed in penetrating the sample is closely related to the material density. Due to the anatomical nature of softwoods, early wood and late wood are separable on the basis of density, with more dense wood (late wood) formed at the edge of the growth ring. Thus, a resistogram appears as a succession of peaks and troughs, corresponding to variations in the penetrability of the early- and latewood in the annual rings.

The relationship between amplitude and wood density values in standing trees of loblolly pine (*Pinus taeda*) depended on two variables fitted to the regression model when determining wood density nondestructively (Isik and Li, 2003). Similar positive results were also reported for *Pseudotsuga menziesii* (Chantre and Rozenberg, 1997), *Pinus pinaster* (Bouffier et al., 2008), and *Eucalyptus globulus* subsp. *pseudoglobulus* (Johnstone et al., 2011) using Resistograph. There are also several reports of the use of Resistograph to measure annual ring sizes and certain mechanical properties such as strength and modulus of elasticity on both sawn wood materials and standing trees (Rinn, 1996; Rinn et al., 1996; Isik and Li, 2003; Lin et al., 2006; Lourenço et al., 2007). Although the device was not very effective for strength determination in some of these studies (i.e. Eckard, 2007), others reported successful results and models that included variables such as wood density (Tsai et al., 2004; Tseng and Hsu, 2008).

The aim of this work was to investigate the applicability of Resistograph for the determination of wood density of sawn spruce lumber.

## 2. Materials and methods

Theoretically, lumber is cut from a log in one of two distinct ways: 1) tangential to the annual growth rings ( $\theta = 0^\circ$ ), producing lumber called, for hardwoods, plain sawn, or flat-sawn for softwoods, or 2) radially to the rings ( $\theta = 90^\circ$ ) or parallel to the rays, producing quarter-sawn lumber for hardwoods, or edge-grained in softwoods. Not all lumber can be cut precisely to fit these definitions. Normally, a piece sawn so that the growth rings, when viewed from the end at an angle of  $45^\circ$  or more ( $\theta = 45^\circ\text{--}90^\circ$ ) with the wide faces, is classified as quarter-sawn, and when the rings are at an angle of less than  $45^\circ$  ( $\theta = 0^\circ\text{--}45^\circ$ ), as plain-sawn (Ross, 2010; Simmons, 2011). The basic working principle of the Resistograph is the transfer of drilling resistance data from a bit of 1.5–3 mm in diameter in the lumber by advanced electronics and mechanical sensors to graphing

the transferred data. This experiment was designed based on the assumption that the amplitude value seen in the resistogram would change according to the positions and sizes of the annual rings; thus, the experiment was designed for lumber cut to the full radial. Preliminary experiments on small-sized samples showed that the correlation between density and amplitude data obtained from radial direction drilling was higher than that from the tangential direction. The models were therefore constructed using data obtained from drilling perpendicular to the annual rings. All measurements were obtained from clear regions of each sample to reduce variability due to defects.

In the study, imported spruce (*Picea abies*) lumber samples were purchased from a local market. Samples were cut into two pieces from pith (Figure 1) to provide samples A and B. Drilling resistance was recorded on samples A and B using an IML-Resistograph F500 S, as shown in Figure 2.

The Turkish standard for wood density determination (Turkish Standards Institution, 1976) requires samples of  $20 \times 20 \times 30$  mm (radial  $\times$  tangential  $\times$  longitudinal). A sampling plan was designed, therefore, for the adjacent area of drilling points (gray area in Figure 1) according to these dimensions. Samples were acclimated at  $20^\circ\text{C}$  and 65% humidity until attaining constant weight and dimensions. Drilling was carried out in the middle section of the samples (Figure 1). After Resistograph measurements, samples for density measurements were cut as shown in Figure 1. Since the cutting process may have resulted in further changes in moisture content (MC), samples were returned to  $20^\circ\text{C}$  and 65% humidity for a further 24 h. MC was measured using a CEM DT-129 electrical moisture meter and its results were confirmed by drying method before and after drilling.

Air dry density was determined as:

$$D_{12} = \frac{M_{12}}{V_{12}}$$

where:

$D_{12}$  is air-dry density ( $\text{g}/\text{cm}^3$ ),

$M_{12}$  is air-dry mass ( $\text{g} \pm 0.001$  g), and

$V_{12}$  is air-dry volume ( $\text{cm}^3 \pm 0.01$  mm) caliper resolution accuracy.

Drilling resistance not only depends on density but also on moisture, which plays an important role (De Ridder et al., 2011). Drill resistance values generally decrease with decreasing MC (Lin et al., 2003). In this work, two models were built using linear regression. In the first model, relationships between density and amplitude values were evaluated to determine the possibility of using the Resistograph in predicting density. For this purpose, samples with less than 1% difference in moisture were used.

MC has a considerable impact on wood density; this parameter was added to Model 2 to strengthen the

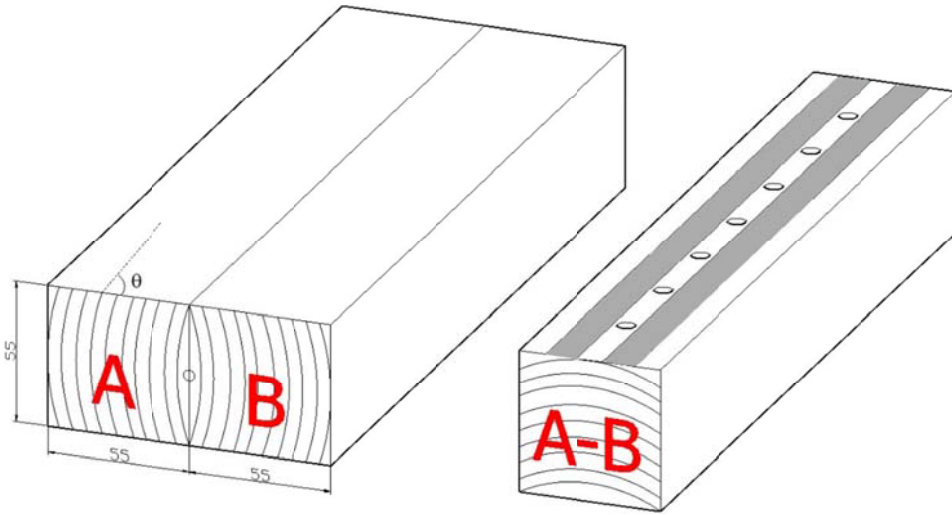


Figure 1. Drilling application and sampling area on study samples (dimensions in mm).

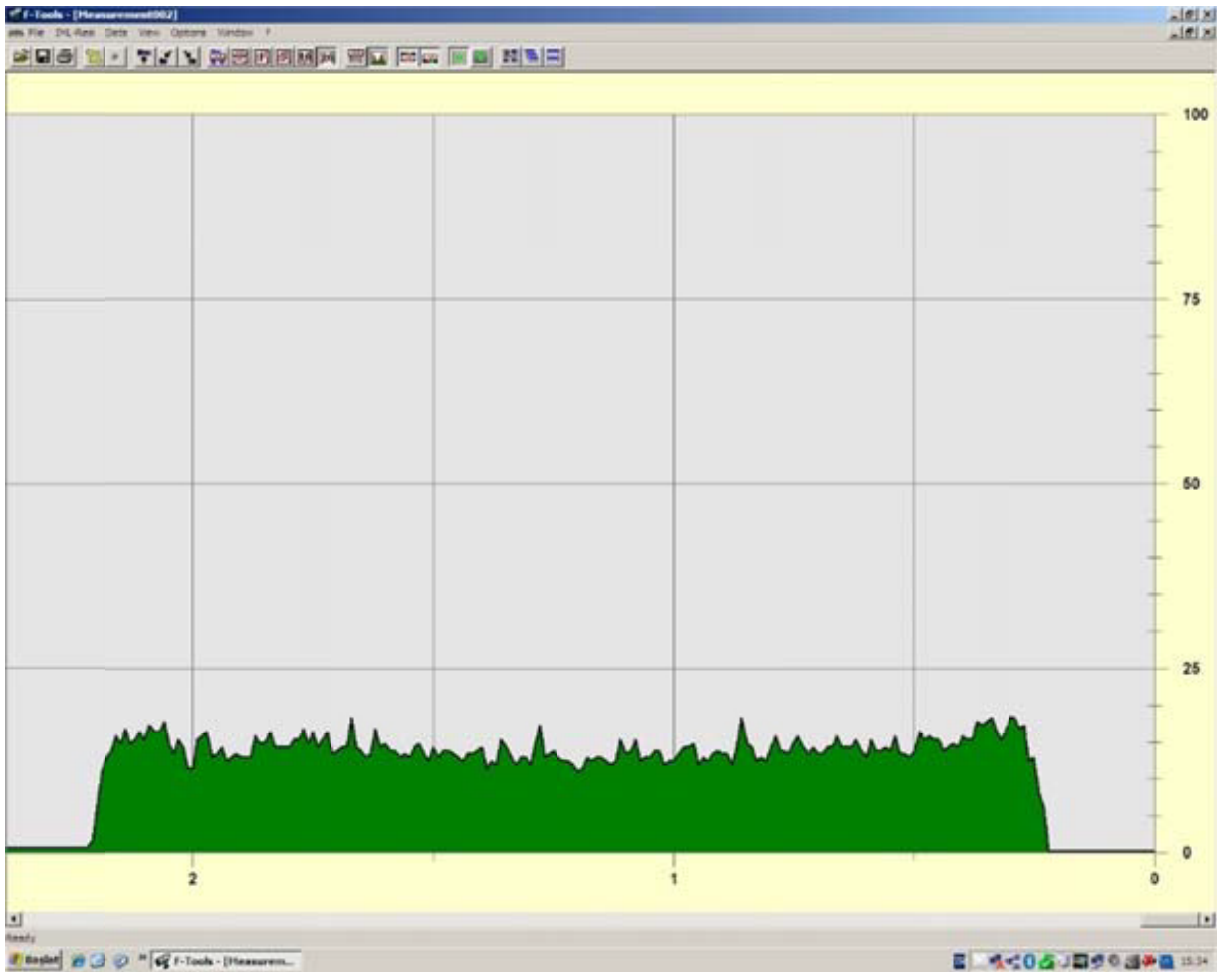


Figure 2. Resistogram of Sample ID 23.

predictions. According to the general wood specific gravity–MC diagram (Kollmann and Côté, 1968), there is a linear relationship from the dry to the air-dry condition. A range of humidity was used, therefore, by applying the required temperature and relative humidity based on the psychrometric chart (Siau, 1995). The MC of the samples varied from 1.1% to 12.8%.

Because the Resistograph could not produce a graph of mean amplitude values for each sample, all data were transferred to ImageJ software and the means were obtained following the first method proposed by Guller (2012) and Acuna et al. (2011) (Figure 3).

The following scripts were written for ImageJ to transfer the Resistograph data to Excel:

```
macro "Rezistograph_to_excel"{
  input_dir = getDirectory("Choose a directory to read from");
  list = getFileList(input_dir);
  var check = 0;
  setBatchMode(false);
  for (i=0; i<list.length; i++) {
    showProgress(i+1, list.length);
    if ((endsWith(list[i], ".bmp")) || (endsWith(list[i], ".jpg")))
```

```
image = input_dir+list[i];
open(image);
run("8-bit");
setAutoThreshold("Default");
setThreshold(0, 158);
setOption("BlackBackground", false);
run("Convert to Mask");
makeRectangle(62, 104, 716, 560);
waitForUser;
run("Analyze Line Graph");
selectWindow("Plot Values");
values = getInfo();
run("Close");
path = input_dir;
shortname = File.nameWithoutExtension;
fullname = shortname+".xls";
fullpath = input_dir+fullname;
f = File.open(fullpath);
print(f, values);
close();
File.close(f);
while (nImages>0) {
  selectImage(nImages);
  close();
```

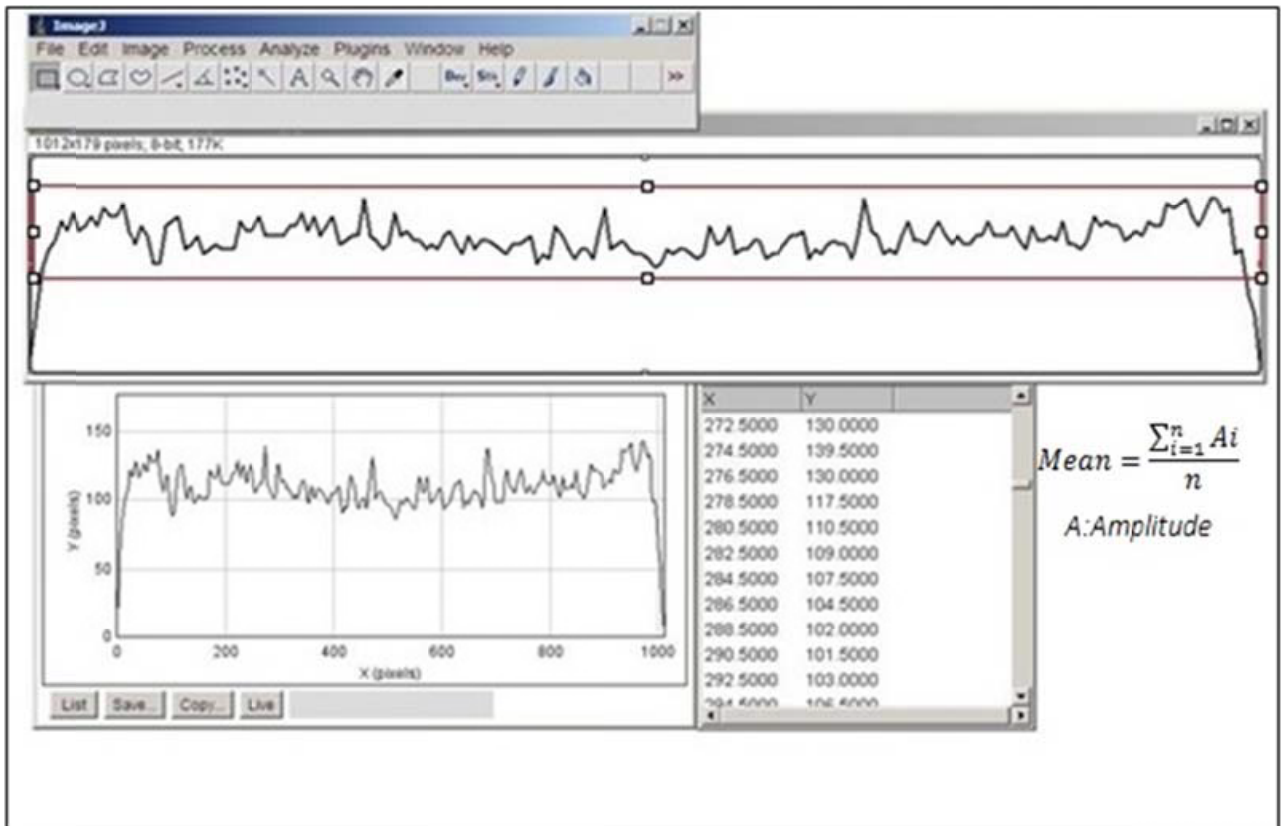


Figure 3. Obtaining numerical data from the resistogram using image analysis.

```

}
check++;
}
}
print(check + " files loaded");
}

```

The least squares technique used to obtain the best-fit in building the model (Miller, 2006) was:

$$y = b + cA \pm e$$

where:  
 $y$  = density (g/cm<sup>3</sup>),  
 $c$  = slope,  
 $A$  = amplitude,  
 $b$  = constant, and  
 $e$  = standard error.

Wood density was determined according to the Turkish standard (Turkish Standards Institution, 1976) to model Resistograph measurements obtained from the same samples. A paired sample t-test was used to compare the two models against the relative control groups (Mee and Chua, 1991).

Thirty wood samples (different from the first wood samples) were used to test Model 1. Model 2 was tested on four different groups (1, 2, 3, and 4) containing a total of 129 samples.

### 3. Results and discussion

There was a good correlation between wood density and Resistograph amplitude data (Table 1). The range of density for the data set was 0.311–0.521 g/cm<sup>3</sup>; the mean value was 0.398 g/cm<sup>3</sup> with a 0.058 standard deviation.

The equation for Model 1 was:

$$y = 0.0519x - 0.1451 \pm 0.006$$

The linear regression model (Model 1) is shown in Figure 4.

For Model 1, density data were not significantly different ( $t = 1.385$ ;  $P = 0.176 > 0.05$ ) (Table 2).

The results obtained here clearly demonstrated that spruce wood density can be predicted nondestructively using the Resistograph, coupled with statistical modeling techniques. However, there are several factors and variables that affect wood density, including species, tree

age, elevation of the forest site, site of origin, MC, and modification process (Rowell and Konkol, 1987; Zobel and Van Buijtenen, 1989; Zobel, 1992; Haygreen and Bowyer, 1996; Bozkurt and Erdin, 1997; Treacy et al., 2000; Guller, 2012). There are also factors affecting the Resistograph readings, such as drilling depth, battery charging amount, bit wear, annual ring structure, ring orientation, and placement. The models, therefore, require improvements, adding in variables that have significant effects, but particularly those that are easily measured on sawn lumber. For example, wood moisture can be considered an important variable. The first focus of this study was to test the utility of the Resistograph. After the results demonstrated that the device can be used in predicting wood density, a second model was tested (Tables 3a, 3b, and 4).

Wood moisture was added as a second independent variable in the model.

Differences between the four groups in Model 2 were insignificant (Table 4;  $P > 0.05$ , 95% confidence level) for all groups and Model 2 was considered successful.

The Resistograph, combined with statistical modeling techniques, shows great promise for the rapid estimation of wood density on large materials. Due to variability in wood density, the reliable use of regression models for predicting this parameter in spruce lumber already in service requires model validation and the addition of other important parameters. Although the work reported here showed high correlations between density and Resistograph data, the regression models generated might provide only approximations when applied to lumber elements in practice because in real weather conditions (temperature and relative humidity) in lumberyards, the MC of the lumber may be higher than in these experiments.

The majority of studies to date have focused on standing trees (i.e. Chantre and Rozenberg, 1997; Gantz, 2002; Isik and Li, 2003; Lima et al., 2007). Work on sawn spruce wood is very limited and the published correlation between density and drilling resistance (Kloiber et al., 2014,  $r^2 = 0.74$ ) was similar to the result in this study. Acuna et al. (2011) reported high correlation values between density and mean amplitude value (adjusted  $r^2$  values of more than 0.80) for six wood species including *Pinus*

**Table 1.** Correlation analysis results for amplitude-density (MC = 12%).

		Amplitude	Density
Amplitude	Pearson correlation	1	0.850**
	Sig. (P)		0.000
	N	38	38

\*\*Correlation is significant at 0.01 level.

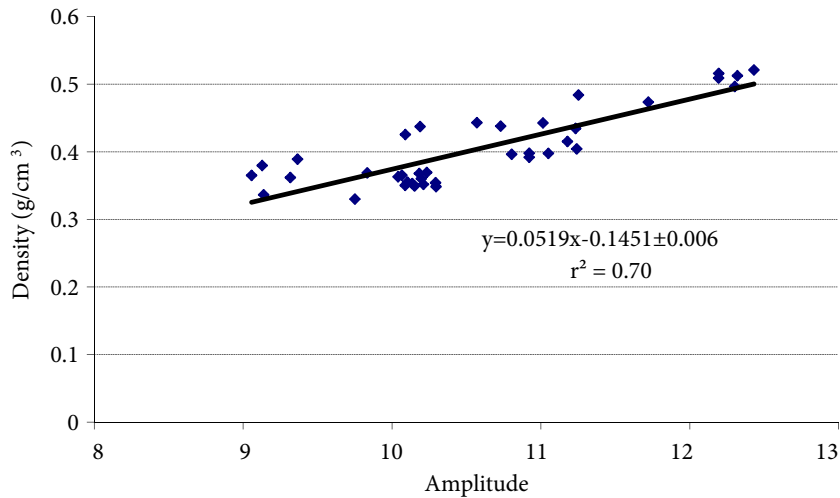


Figure 4. Linear Model 1 for predicting wood density.

Table 2. Paired sample t-test for testing-training wood density.

	Mean	Standard deviation	Standard error	t	Degrees of freedom (df)	Significance (P)
Density(test) – density(Model 1)	0.008	0.031	0.006	1.385	29	0.176

Table 3a. Statistics for Model 2 ( $y = 1.197 - 0.078A + 0.001 \times MC + 0.0244$ ).

Model	R	R square	Adjusted R square	Std. error of the estimate	Change statistics				
					R square change	F change	df1	df2	Sig. F change
2	0.852*	0.726	0.722	0.0244	0.726	165.812	2	125	0.000

Dependent variables: Density, MC (moisture content, MC is set in the model as a % value, e.g., if 10%, set in the model as 10), A (amplitude).

Table 3b. Statistics for Model 2.

Model 2	Unstandardized coefficients		Standardized coefficients	t	Sig.	95% Confidence interval for B		Correlations			Collinearity statistics	
	B	Std. error	Beta			Lower bound	Upper bound	Zero-order	Partial	Part	Tolerance	Variance inflation factor (VIF)
(Constant)	1.197	0.051		23.631	0.000	1.097	1.297					
Amplitude (A)	-0.078	0.005	-0.821	-16.753	0.000	-0.087	-0.069	-0.848	-0.832	-0.784	0.913	1.096
Moisture content (MC)	0.001	0.001	0.091	1.864	0.065	0.000	0.003	0.334	0.164	0.087	0.913	1.096

*sylvestris*, *Pinus nigra*, *Pinus pinaster*, *Castanea sativa*, *Juglans regia*, and *Quercus robur*. Feio et al. (2007) found a high correlation between drilling resistance and density

in chestnut lumber ( $r^2 = 0.81$ : for prediction of density of new samples not involved in the correlation development), results that were supported by Faggiano et al. (2009),

**Table 4.** Paired sample t-test for testing-training wood density.

Paired groups	Mean	Std. deviation	Std. error mean	Lower	Upper	t	df	Sig. (2-tailed)
1- Model 2	0.003	0.012	0.002	-0.002	0.007	1.285	29	0.209
2- Model 2	-0.001	0.027	0.005	-0.011	0.009	-0.182	29	0.857
3- Model 2	-0.003	0.022	0.004	-0.011	0.004	-0.907	31	0.372
4- Model 2	0.003	0.031	0.005	-0.011	0.01	-0.097	36	0.923

although at lower correlation ( $r^2 = 0.67$ ). In contrast, De Ridder et al. (2011) found lower correlation for *Terminalia superba* and Lin et al. (2003) found moderate correlations for *Taiwania cryptomerioides* between Resistograph data and density of lumber. Factors affecting wood density and Resistograph readings, such as MC, drilling depth, annual ring structure, ring orientation, and positioning, possibly lead to differing results. The results reported here are in accordance with previously published work on spruce wood and clearly demonstrate that the correlation between drilling resistance and density is higher in the radial (perpendicular to annual rings) than in the tangential (parallel to annual rings) direction. This is because other angles of drilling are affected by friction (Nowak et al., 2016).

In conclusion, drilling resistance, and the Resistograph device in particular, appears to be a very promising method

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