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In-situ density estimation by four nondestructive techniques on Norway spruce from built-in wood structures

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Abstract: Needle penetration resistance (NPR), screw withdrawal resistance (SWR), core drilling (CD) and drilling chips extraction (DCE) are nondestructive and semi-destructive techniques used to estimate density in timber structures. In most of the previous studies, these techniques were tested in clear sawn timber and clear specimens. The goal of the present paper is to study the relationship between density and these techniques by means of five different devices in whole pieces of timber from built-in engineering structures, which are from 12 4.5-m long structural timber joists of Norway spruce from a 19th century building in Barcelona (Catalonia, Spain). Although determination coefficients (R^2) for density estimation models were lower than those from clear timber, the results obtained confirmed that these four techniques are suitable for *in-situ* density estimation of woods in buildings. The best results were obtained by CD (the bigger the bit, the higher the correlation), followed by DCE, and SWR. The worst correlation was found for NPR devices, but the results could be probably improved with more measurements.

Keywords: core drilling (CD), drilling chips extraction (DCE), needle penetration resistance (NPR), nondestructive testing (NDT), probing, screw withdrawal resistance (SWR)

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Introduction

Nondestructive testing (NDT) methods (needle and drill penetration resistance, screw and nail withdrawal resistance and core drilling) are mainly used to estimate density in standing trees and logs (Rinn et al. 1996; Ponneth et al. 2014; da Silva et al. 2017), and in structural timber (Görlacher 1987; Bobadilla et al. 2007; Esteban et al. 2009; Íñiguez-González et al. 2015a; Llana et al. 2018). Hardness has a good relationship to density (Ceccotti and Togni 1996). Sclerometers are also suited to density estimation (Soriano et al. 2015). According to Carballo et al. (2009), the most common probing techniques in Spain for density estimation are NPR, performed with the instrument Pilodyn 6J Forest (Proceq, Schwerzenbach, Switzerland), and SWR (instrument SWR Meter, Fakopp Enterprise Bt., Sopron, Hungary). In recent years, the techniques of core drilling (Montón 2012) and drilling chips extraction were also tested successfully for density determination (Martínez 2016). The most relevant approaches NPR, SWR, CD and DCE are summarized in the following:

Needle penetration resistance (NPR): The Pilodyn device was developed in Sweden in the 1970s and is based on the NPR method. The instrument operates by shooting a blunt pin into wood with an exactly known energy, after which the penetration depth is read on a scale (Hoffmeyer 1978). It is popular for testing standing trees (Cown 1978), poles (Morrell et al. 1994), and built-in wood structures (Görlacher 1987). The Wood Pecker test hammer (DRC, Ancona, Italy) measures the NPR depth in wood after one or several constant-energy strikes. The main difference between this and other NPR testers is that it is possible to strike the needle several times and record penetration depth after each strike.

Screw withdrawal resistance (SWR): SWR force is known to be correlated with sawn timber density (Cockrell 1933) and timber product density (Shalbafan et al. 2013). The SWRM is a portable device that was developed in the 1990s (Divós et al. 1994) and it was successfully applied for density estimation of several Spanish-sourced species.

Core drilling (CD): The CD technique, based on the increment borer developed by Pressler (1866), has been used for several decades for specific gravity estimation in standing trees (Walters and Bruckmann 1964; Bergsten et al. 2001; Moreno-Chan et al. 2010). Since the end of the last century, the compressive strength of small diameter cores from built-in wood structures have been tested, and it is also used as an estimator of density (Kasal 1997). CD is a semi-destructive technique leading to density estimation of samples, which is also suitable for species identification. Cylindrical specimens (5–22 mm ∅) are removed from timber using a commercial core bit. According to Kasal and Tannert (2010), the holes left by CD are smaller than some natural defects, such as knots, and does not compromise strength. Falk et al. (2003) performed a four-point bending test on Douglas-fir specimens with 25.4 mm diameter holes in their midspan axis at different heights. A hole in the compression zone had no significant influence on bending strength.

Drilling chips extraction (DCE): Paul and Baudendistel (1943) described a procedure for the *in-situ* determination of specific gravity from auger chips. A new device known as the RML Wood Extractor (Timber Construction Research Group, GICM-UPM, Madrid, Spain) was developed by Martínez (2016) based on the DCE technique (patented by Martínez and Bobadilla 2013). Bobadilla et al. (2013) presented a prototype of the instrument in a wood NDT conference in Madison. The device was designed to be coupled to a commercial drill to collect all of the chips produced during drilling inside a paper bag filter. Density is determined from the mass of chips and the volume of the hole.

According to several authors (Bues et al. 1987; Bobadilla et al. 2007; Íñiguez 2007; Calderón 2012; Martínez 2016) there are no significant differences between radial (R) and tangential (T) probing measurements, aside from the fact that it is rarely possible to select the probing direction *in-situ*. Most of the previous research was done in clear timber (Salamanca 2017; Martínez et al. 2018) or in slices from new timber free of singularities (Bobadilla et al. 2007; Íñiguez et al. 2010; Casado et al. 2012; Montón 2012; Montero 2013; Íñiguez-González et al. 2015b). However, wood as part of built-in structures was seldom used free of singularities (Casado et al. 2012; Morales-Conde et al. 2014).

Obviously, the measurements in clear timbers or clear slices provide results with less scattering than in less homogeneous woods with singularities, such as knots with twice as high densities compared to clear wood. Studies with clear timber result in the lowest R^2 using NPR, followed by SWR, while the highest and best R^2 values can be achieved by CD and DCE, but a statistically relevant comparison of the techniques are not yet available. Specific research is needed to make the results of the known techniques comparable, and this was the purpose of the present study.

Materials and methods

Materials: Twelve large cross-section Norway spruce joist specimens from a dismantled 19th century building in the Sants-Montjuïc district of Barcelona (Catalonia, Spain) were tested. Their average dimensions: 4520 mm length with a cross-section of 76×226 mm². Each specimen was microscopically identified as Norway spruce [*Picea abies* (L.) Karst.] in the Timber Technology Laboratory of the School of Forest Engineering and Natural Resources, UPM (Madrid, Spain). Specimens were stored in the laboratory until a constant MC had been achieved. The equilibrium moisture content (EMC) was determined by the oven dry method according to standard EN 13183-1 (2002) based on specimen slices free of knots and resin pockets according to EN 408 (2012). The mean EMC of the 12 specimens was 11.4% (10.9–12.7%). Furthermore the mass and dimensions of whole specimens were recorded to determine density as mass/volume ratio with a mean density of 434 kg m^{-3} (402–510 kg m^{-3}).

NDT experiments: Five different NDT variables were measured only once in each specimen (whole piece) avoiding areas close to the pith and other singularities such as knots or resin pockets and not taking into account R or T directions: (1) NPR depth, with the Pilodyn 6 J Forest commercial device (Proceq, Schwerzenbach, Switzerland) (Figure 1a). This consists of a calibrated spring that releases a 2.5 mm diameter steel needle with a constant energy of 6 J and the penetration depth of it is measured in mm. (2) NPR depth, with the commercial device Wood Pecker (DRC, Ancona, Italy) (Figure 1b). This modified sclerometer inserts a 2.5 mm diameter steel needle with constant energy, striking several times. In this study, the penetration depth was measured in mm after one, three and five strikes. (3) SWR force was measured with the commercial device SWRM (Fakopp Enterprise Bt., Sopron, Hungary) (Figure 1c). The screw applied was a Heco-Fix-Plus (Heco-Schrauben GmbH & Co. KG, Schramberg, Germany) with a Spax (PZD) type head. It is a yellow zinc plated, 4-mm diameter 70-mm long screw, with a penetration depth of 20 mm. SWR force is measured in kN. (4) The mass and volume of cylindrical cores were measured by means of two commercial core bits (Figure 1d) with external diameters of 14 and 22 mm and internal ∅ of 10 and 16 mm, respectively. (5) The mass of chips was measured by a RML Wood Extractor device (GICM-UPM, Madrid, Spain) coupled to a commercial PSB 50 drill (Bosch, Gerlingen, Germany) (Figure 2). An 8 mm ∅ bit was drilled into a standard 47 mm depth into the wood specimens (hollow volume is known) combined with vacuum chip collection.

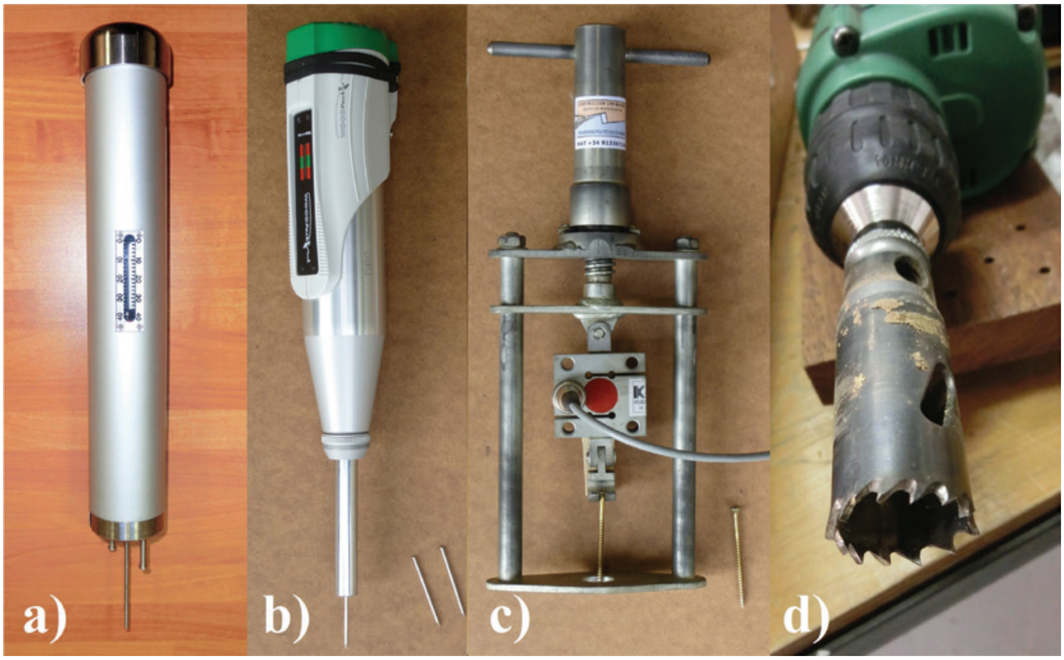

Figure 1: Probing devices used.
(a) Pilodyn 6J Forest, (b) Wood Pecker, (c) SWRM, (d) core drill.

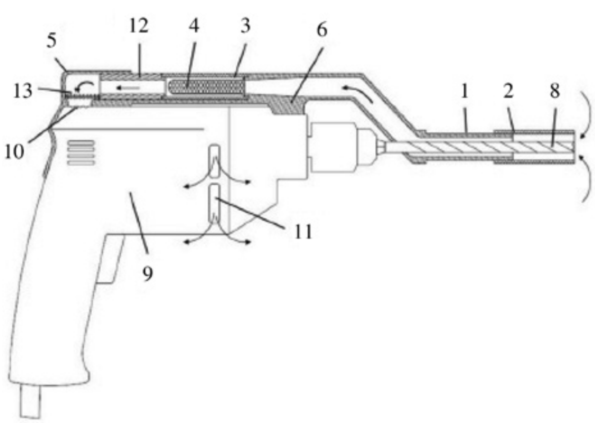

Figure 2: RML Wood Extractor (1) coaxial pipes, (2) telescopic system, (3) cartridge, (4) paper filter bag, (5) enveloping structure, (6) clamp, (7) spring, (8) drill bit, (9) power drill, (10) air intake, (11) side holes, (12) telescopic tube, (13) spring. (Republished from Martínez 2016 with permission.)

Results and discussion

Table 1 summarizes EMCs, density and NPR depth obtained by the Pilodyn and Wood Pecker, and the SWR force via SWRM, and the densities determined with two CDs and the chip mass approach with the RML Wood Extractor device. As EMCs in Table 1 are really close to 12%, thus no MC correction factors were applied to density and NDT measurements. Coefficients of variation (COV) of mean values are similar for the devices, except for the SWRM, which is higher as was found by several other authors, namely Montón (2012) in radiata pine, Llana (2016) in Salzmann pine and Martínez (2016) in several species. This could be partly explained by the influence of operators, as the hand turning speed of SWRM affects the results.

To estimate the density from different devices, simple linear regression analyses were performed (Eq. 1, Table 2 and Figure 3):

$$\text{Den} = a * \text{VAR} + b, \tag{1}$$

where Den (kg m^{-3}) is the specimen's density; VAR is the variable measured with NPR depth (mm), SWR is the force (kN), core density (kg m^{-3}) or chip mass (g).

Density estimation results with Pilodyn gave a R^2 (22%) that is lower than those found in the literature for sawn timber slices (from 31 to 61%). Bobadilla et al. (2007) estimated of 395 pieces' density of the species radiata, Scots and Salzmann pine with a determination coefficient (R^2) of 39%. Íñiguez et al. (2010) found a higher density coefficient (61%) based on 266 pieces of the same three species and maritime pine. Montón (2012) reported a R^2 of 31% for density estimation of 60 radiata pine specimens. Montero (2013) obtained a R^2 of 32% with 218 new timber specimens of Scots pine. Llana (2016) reported a R^2 of 56% using new specimens of radiata, Scots, Salzmann and maritime pine.

Table 1: EMC, density, NPR depth, SWR force, core density and chip mass results.

	MC	Density	Pilodyn	Wood Pecker			SWRM	Core drill		RML
Specimen no	EMC (%)	Density (kg m^{-3})	NPR depth (mm)	1 strike NPR depth (mm)	3 strikes NPR depth (mm)	5 strikes NPR depth (mm)	SWR force (kN)	Bit Ø 14 mm density (kg m^{-3})	Bit Ø 22 mm density (kg m^{-3})	Chips mass (g)
1	11.5	402	16.0	10.7	21.7	28.5	1.00	410	418	1.05
2	11.0	412	18.0	10.2	18.3	23.7	1.13	429	416	1.21
3	10.9	413	16.0	11.3	20.1	26.2	1.14	452	414	1.02
4	11.4	420	14.0	8.9	17.7	23.9	1.31	462	448	1.14
5	11.2	420	13.0	6.7	13.7	18.5	1.34	434	462	1.21
6	11.0	426	14.0	10.3	18.2	22.7	1.12	474	458	1.24
7	11.7	434	16.0	8.8	16.2	21.6	1.35	501	494	1.25
8	11.9	435	13.0	10.5	17.3	22.4	1.17	464	472	1.16
9	11.8	438	12.0	9.9	16.6	21.2	1.79	496	467	1.13
10	12.7	439	12.0	9.4	16.3	19.0	1.26	484	489	1.28
11	10.9	463	14.0	10.1	17.1	21.5	1.07	471	486	1.24
12	11.0	510	13.0	8.7	15.3	19.8	2.11	630	711	1.49
Mean	11.4	434	14.3	9.6	17.4	22.4	1.32	475	478	1.20
(COV)	(4.8)	(6.6)	(13.1)	(12.7)	(12.1)	(12.9)	(24.5)	(11.7)	(16.5)	(10.1)

Table 2: Coefficients for Eq. 1 (Den = a*VAR + b) and R^2 and P-values of the predictions.

Device	Variable VAR	a	b	R^2 (%)	P-value
Pilodyn	NPR depth	−7.25	538	22	0.12
Wood	1 strike NPR depth	−5.77	490	6	0.44
Pecker	3 strikes NPR depth	−7.25	560	28	0.08
	5 strikes NPR depth	−5.70	562	33	0.05
SWRM	SWR force	64.69	349	53	0.01
Core drill	Bit Ø 14 mm core dens	0.47	209	84	0.00
	Bit Ø 22 mm core dens	0.34	270	89	0.00
RML	Chips mass	198.97	195	70	0.00

The Wood Pecker R^2 data are higher with more strikes (from 6 to 33%), but these data are still much lower than the 75% obtained by Salamanca (2017) with three strikes in small clear wood specimens from 10 species (black poplar, European oak, iroko, missanda, sweet chestnut, western red cedar, radiata, Scots, Salzmann and maritime pine).

SWRM R^2 (53%) is within the range cited by other authors (49–74%). Casado et al. (2005) estimated the density of 39 joists of Scots pine from a built-in structure, with a R^2 of 62%. Bobadilla et al. (2007) and Íñiguez et al. (2010) reported a R^2 of 49% and 61%, respectively, in radiata, Scots and Salzmann pine new structural timber specimens. Casado et al. (2012) reported a 74% R^2 on 217 new timber slices of black poplar. Íñiguez-González et al. (2015b) found a R^2 of 57% in 150 new timber specimens of radiata pine. Llana (2016) obtained a 68% R^2 for radiata, Scots, Salzmann and maritime pine.

R^2 CD results are slightly higher for bigger cores (84–89%), and they are similar to the 88% and 80% data reported by Montón (2012) and Íñiguez-González et al. (2015b), respectively, and higher than 48% found by Morales-Conde et al. (2014).

Density estimation from chip mass gave a 70% R^2, which is lower than the 84% reported by Martínez et al. (2018) in clear wood specimens of radiata, Scots, Salzmann and maritime pine. In general, the higher is the semi-destructive character of the measurement, the greater is the correlation. At higher material removal rate, the density estimation improves.

As the P-value in the analysis of variance (ANOVA) in the Table 1 is <0.05 for SWRM, core drill and RML, there is a significant relationship between density and the variables studied at a 95% confidence level. However, the confidence level is lower for the Pilodyn and Wood Pecker instruments. In the case of the Wood Pecker the confidence level rises with increasing numbers of strikes.

Figure 3 shows the linear regressions for density estimation for each device with 12 measurements, one from

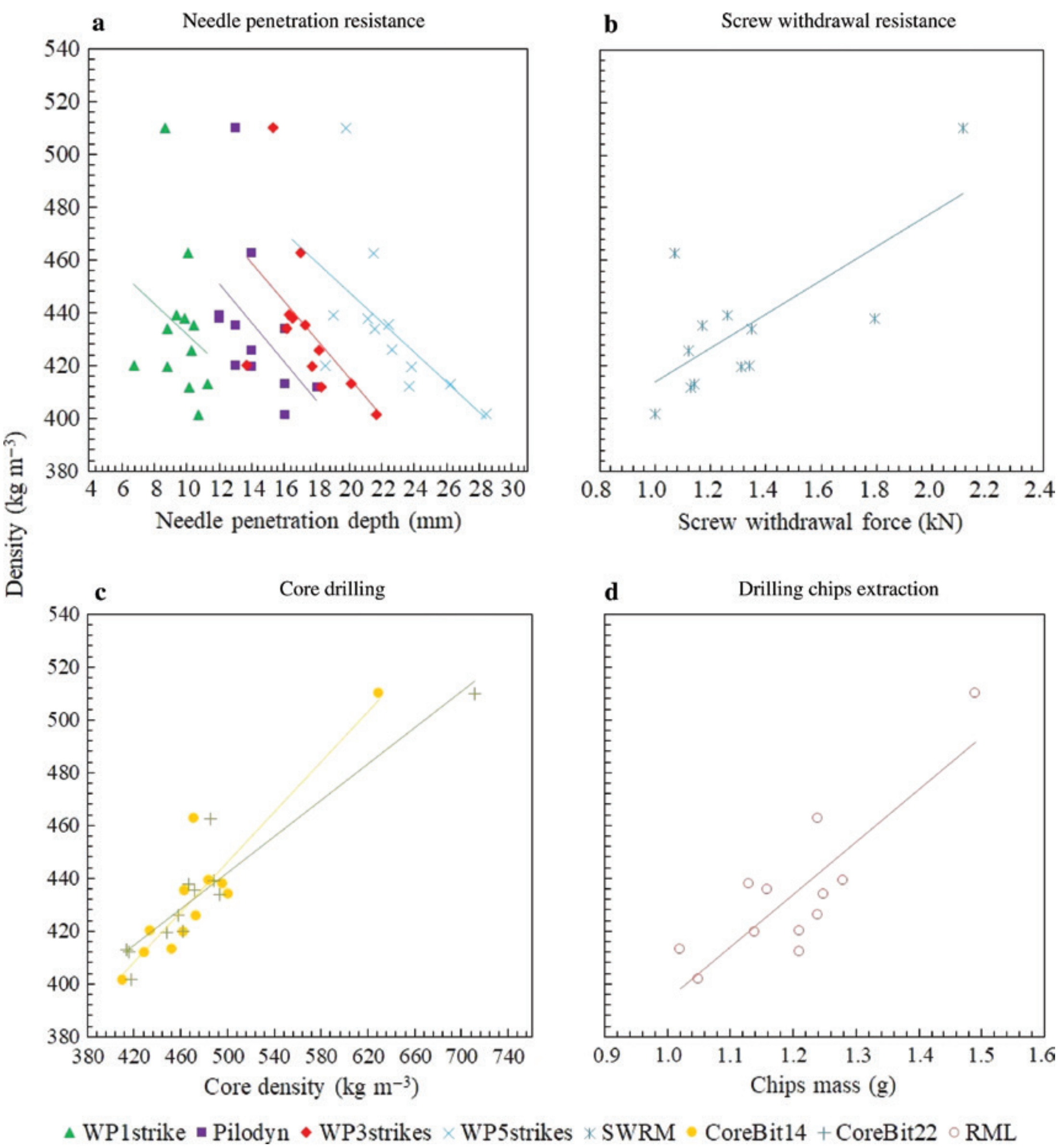

Figure 3: Linear regressions.
(a) Wood Pecker and Pilodyn, (b) SWRM, (c) core drill, (d) RML Wood Extractor.

each specimen. One specimen showed a higher density (510 kg m^{-3}) compared with the mean value of the other 11 pieces (427 kg m^{-3}) in spite of the fact that the same species were identified microscopically. Although this specimen was analyzed in detail to detect abnormal characteristics (ring growth, resin content, etc.), no reason for the deviation was found.

Table 3 shows exactly the same mean density as was expected, because Eq. 1 was created based on these data. When Eq. 1 is applied on every single specimen, the lowest errors are found for the CD method as was expected, because the real density is estimated from the density of a core. RML Wood Extractor, SWRM and Wood Pecker 3 and 5 strikes deliver error values double than the core, being the highest ones achieved with Pilodyn and Wood Pecker 1. According to Table 2, Wood Pecker R^2 is low and SWRM R^2 is medium, but the errors are similar to RML with a high R^2.

If Eq. 1 is applied to every single specimen, estimated densities can be obtained. Figure 4 shows the differences between measured and estimated densities. In the case of needle penetration devices (Figure 4a), all densities are overestimated in the range of low real densities, but are more accurate around 430 kg m^{-3}. Figure 4b shows that SWRM also overestimates low densities and that CD is the most accurate instrument, especially if equipped with a 22 mm bit.

Table 3: Measured and estimated densities.

	Density (kg m⁻³)	Estimated density (kg m⁻³) and error (%)							
			Wood Pecker				Core drill		
Spec. no	Mass/volume	Pilodyn	1 strike	3 strikes	5 strikes	SWRM	Bit Ø 14 mm	Bit Ø 22 mm	RML
1	402	422	428	403	400	414	403	414	404
		5.0	6.6	0.3	0.5	3.1	0.4	3.0	0.6
2	412	407	431	428	427	422	412	413	436
		1.2	4.6	3.8	3.6	2.5	0.1	0.2	5.8
3	413	422	425	414	413	423	423	412	398
		2.1	2.8	0.3	0.1	2.4	2.5	0.2	3.6
4	420	436	439	432	426	434	428	424	422
		3.9	4.5	2.9	1.5	3.4	2.0	1.1	0.6
5	420	443	451	461	457	436	414	429	436
		5.6	7.3	9.7	8.7	3.8	1.3	2.1	3.8
6	426	436	430	428	433	422	433	428	442
		2.4	1.0	0.6	1.6	1.0	1.7	0.4	3.7
7	434	422	439	443	439	436	446	440	444
		2.9	1.1	2.0	1.2	0.6	2.8	1.3	2.3
8	435	443	429	435	434	425	429	432	426
		1.8	1.4	0.2	0.3	2.4	1.5	0.7	2.2
9	438	451	433	440	441	465	444	430	420
		2.9	1.2	0.5	0.8	6.2	1.4	1.7	4.1
10	439	451	436	442	453	431	438	438	450
		2.6	0.8	0.7	3.3	1.9	0.2	0.3	2.4
11	463	436	431	437	440	418	432	437	442
		5.7	6.7	5.6	5.0	9.6	6.6	5.5	4.5
12	510	443	440	449	449	486	508	515	492
		13.1	13.8	11.9	11.9	4.8	0.5	0.9	3.6
Mean Dens.	434	434	434	434	434	434	434	434	434
(COV)	(6.6)	(3.1)	(1.6)	(3.5)	(3.8)	(4.8)	(6.1)	(6.2)	(5.5)
Mean error (%)		4.1	4.3	3.2	3.2	3.5	1.7	1.4	3.1

Data from Eq. 1.

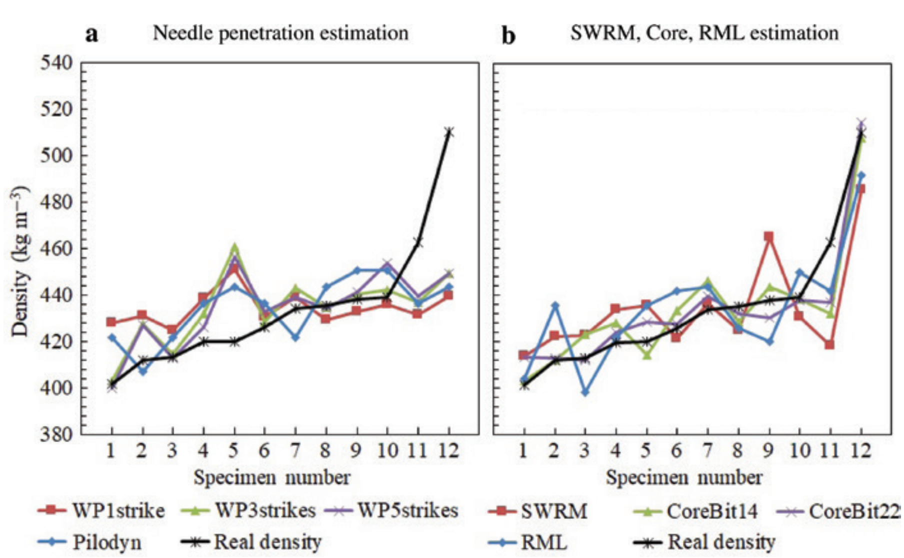

Figure 4: Experimental and estimated densities by different devices. (a) Wood Pecker and Pilodyn, (b) SWRM, core drill and RML Wood Extractor.

In general, the more material that is removed, the higher is the correlation as already stated. This was also seen on the CD approach, where bigger cores resulted in better correlation data. Core drilling is the only method that estimates real density from other density (core density), and R^2 data are higher and errors are lower than in case of other methods.

From a practical point of view, the assessment of built-in structures is more time consuming and costly. The less reliable density estimations were found by Pilodyn (with only one measurement per specimen), but this device is the fastest. In future research works, more than one measurement should be performed with Pilodyn to achieve a more reliable statistical evaluation of this instrument. Görlacher (1987) showed an R^2 increment from 41% from one measurement to 85% for 16 measurements on clear Norway spruce timber. In the case of the Wood Pecker, at least five strikes are recommended. As the other devices delivered better results, which are similar to those in the literature, it can be safely concluded that only one measurement per specimen is needed to estimate density based on the devices SWRM, core drill and RML Wood Extractor.

Conclusions

All of the NDT techniques studied (NPR, SWR, CD and DCE) are suitable for *in-situ* density estimation of built-in timber structures, although correlations are lower than on clear specimens. Semi-destructive systems with higher degree of degradation gave better results than the less destructive ones. CD gave the best R^2 (84–89%, the bigger the bit, the larger the R^2), which was closely followed by the DCE principle performed with the new RML Wood Extractor device (70%). SWR with SWRM gave a R^2 (53%) similar to data presented in the literature. However, NPR showed poor R^2 values and lower confidence levels. In the case of the Wood Pecker, more strikes gave better R^2 (33% for five strikes) and higher confidence levels, while the Pilodyn results in the worst R^2 (22%). Another important factor that should be taken into account is the time-cost variable. Although the Pilodyn gave the worst R^2 (22%) and a relationship with density at a confidence level of 87%, it is the least time-consuming method and should be studied to find out how to improve its performance.

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