

Article

Assessing the Density of Wood in Heritage Buildings' Elements Through Expedited Semi-Destructive Techniques

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Featured Application

The research presented and justified in this text aims to provide agents involved in the conservation and refurbishment of old timber elements in buildings with a correlation table for interpreting the readings obtained with penetration resistance testing equipment.

Abstract

Historically, wood has been among the main materials used in heritage buildings. However, the species and mechanical properties of these elements are often unknown. This uncertainty complicates safety assessment calculations, aggravated by the natural variability of the wood properties. The aim of this work is to assess the density of wooden elements in service using semi-destructive techniques that retain the integrity of structural elements. This research had two phases. First, penetration resistance tests were carried out on laboratory scale on *Pinus sylvestris* L. wood samples taken from 18th, 19th, and 20th century heritage buildings in Lisbon, Portugal. Later, a field study was carried out on wooden elements from the same buildings, involving needle penetration, core drilling, and moisture content determination tests. The laboratory test results showed a strong correlation between the needle penetration depth and wood density, with an R^2 value of 0.76. The results of the field study indicated that the density estimated by the needle penetration test correlated effectively with the measured density of extracted cores after moisture correction, with an R^2 of 0.99. In conclusion, the experimental results confirm that penetration resistance and moisture tests are reliable and practical for estimating wood density under in-service conditions.

Keywords: density; semi-destructive test; needle penetration resistance; core drilling; Scots pine



Academic Editor: Federica Antonelli

Received: 11 June 2025

Revised: 22 June 2025

Accepted: 2 July 2025

Published: 5 July 2025

Citation: Henriques, D.F.; Şen, A.U.; Gomes, M.d.G. Assessing the Density of Wood in Heritage Buildings' Elements Through Expedited Semi-Destructive Techniques. *Appl. Sci.* **2025**, *15*, 7552. <https://doi.org/10.3390/app15137552>

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1. Introduction

Wood has always been a versatile material throughout human evolution, initially used as a solid fuel, tools, or weapons. One of the oldest wood samples was discovered in a brown coal mine in Germany in 1995 and dated to be 400,000 years old [1]. Wood has also been frequently used as construction material for ships and buildings [2,3]. Despite its versatility, wood has a major limitation: it is predominantly an organic material that can undergo deterioration under certain conditions, such as exposure to humidity, ultraviolet

radiation, and mechanical stress [4,5]. These conditions may induce a disintegration of wood's structure, significantly reducing its mechanical properties, particularly after an attack by fungi, insects (beetles and termites), or bacteria. As a result, frequent inspections of wooden structures in ancient buildings are essential not only to evaluate the safety of the structures but also to preserve and restore cultural heritage buildings [6–8]. In heritage buildings, the used timber species is often unknown, which further complicates the assessment of the mechanical properties and stiffness of structural wood members, considering the high variability of wood properties, even in the same wood species [4].

The mechanical properties of wood can be evaluated at the laboratory scale using small, defect-free (free of knots, cracks, reaction wood, etc.), and conditioned wood samples by following relevant norms such as DIN EN 52182 [9], ISO 13061 [10], or EN 384 [11]. Alternatively, this evaluation may be performed using auxiliary non-destructive (NDT) visual grading and advanced methods, semi-destructive or low-destructive techniques (SDT), or a combination of these approaches [12–17]. The SDT techniques are particularly relevant in the analysis of ancient woods, standing trees, and logs [7,18–21]. Starting from 1950s, several advanced non-destructive techniques (NDTs) were introduced to study wood, including X-ray radiation diffraction, X-ray computer tomography (CT), near infrared spectroscopy (NIR), infrared spectroscopy (FTIR), ultrasound techniques, neutron imaging (NI), active thermography, etc. [18,22–26]. These techniques have proven highly effective for the detailed characterization of wood structures, but they are often costly, require surface preparation, and are usually unsuitable for an in situ analysis. On the other hand, mechanical wood inspection techniques such as drilling resistance (DR), needle penetration resistance (NPR), screw withdrawal resistance (SWR), and core drilling (CD), which are SDTs, offer advantages over the advanced NDTs, such as a lower cost, rapid application, and in situ application [14]. Moreover, it is easier to evaluate the results of mechanical wood inspection techniques in wood constructions compared with the often complex interpretation required for advanced NDTs [27].

Density is one of the key indicators of wood strength (the other important indicators being moisture content, anatomical features, and chemical composition) [4]. Generally, the density of wood is directly proportional to its mechanical strength [4]. Conversely, moisture content (u) is inversely related to wood strength below the fiber saturation point ($u = 30\%$), which represents the maximum u in which wood is usually used [4]. Anatomical features of wood, such as the ring width and the proportions of latewood and juvenile wood, influence the density profile [28]. Chemical composition also plays a critical role in wood strength because the density as well as the linking and spatial arrangement of cellulose, hemicelluloses, and lignin differ significantly; thus, their relative content directly affects mechanical performance [4,5]. Previous studies demonstrated that density and the holocellulose (cellulose + hemicelluloses) content can serve as indicators of the residual strength in wood structures [29].

Five different densities can be defined for wood, including oven-dry density, green density (wet density), basic density (dry mass over wet volume), air-dry density (the mass and volume of wood is calculated after conditioning at 20 °C and 65% relative humidity), and apparent density (the wood density is calculated without a specification of the humidity). Of these density classes, usually the air-dry density or basic density is used for practical purposes [21]. Previously, studies have shown that density of wood is proportional to its hardness, and NPR and SWR tests were developed to determine the density of wood [30]. Although these tests were sensitive to the moisture content (u) in wood [30–32], they are considered to be reliable indicators of wood density, particularly in structural wood [14,19,33]. A study using Scots pine wood from an 18th century building in Madrid indicated a determination coefficient of 59% [34,35]. These results imply that

additional measurements and improved correlations are required to better estimate wood density using needle probe tests, particularly in the assessment of wood quality in cultural heritage buildings.

The objectives of this work are to estimate the density of Scots pine (*Pinus sylvestris* L.) wood used in Lisbon in the buildings of 18th, 19th, and 20th centuries with NPR testing and to obtain a correlation between the NPR results and wood density that can be used for practical applications. Beams of Scots pine were analyzed in situ by Pilodyn 6 J® (Proceq, Schwerzenbach, Switzerland) needle penetration resistance and core drilling tests. Needle penetration calibration data was obtained from laboratory tests and density correlations between the in situ NPR test (estimated density) and core drilling tests (actual, measured, or real density) were established for the first time.

2. Materials and Methods

2.1. Materials

A set of pine wood beams was collected from various buildings that were demolished in central Lisbon between the mid-18th and mid-20th centuries for laboratory testing (Figure 1a). Five beams were selected from this set of wooden structural elements based on the criterion that more than 90% of their cross-section was defect-free. The selected beams exhibited a limited number of defects, including cut defects, metal nails, resin, and some knots (Figure 1b). All the selected beams were identified as Scots pine (*Pinus sylvestris* L.) and had been in use for over 200 years.



Figure 1. (a) Wooden elements from old buildings. (b) Preparing the wood beams for testing.

2.2. Determination of the Air-Dry Density

Samples measuring $25 \times 55 \times 200$ mm were obtained by cutting the beams. The process of beam cutting and specimen geometry are shown in Figure 2a. These specimens were then submitted to moisture content (u) stabilization under a relative humidity (RH) of $65 \pm 5\%$ and a temperature of 20 ± 2 °C (Figure 2b) according to EN 384 [11]. These environmental conditions lead to a wood moisture content of around 12%, which was considered the reference.

After stabilization, the weight and dimensions of each sample were recorded, and the corresponding density was measured.

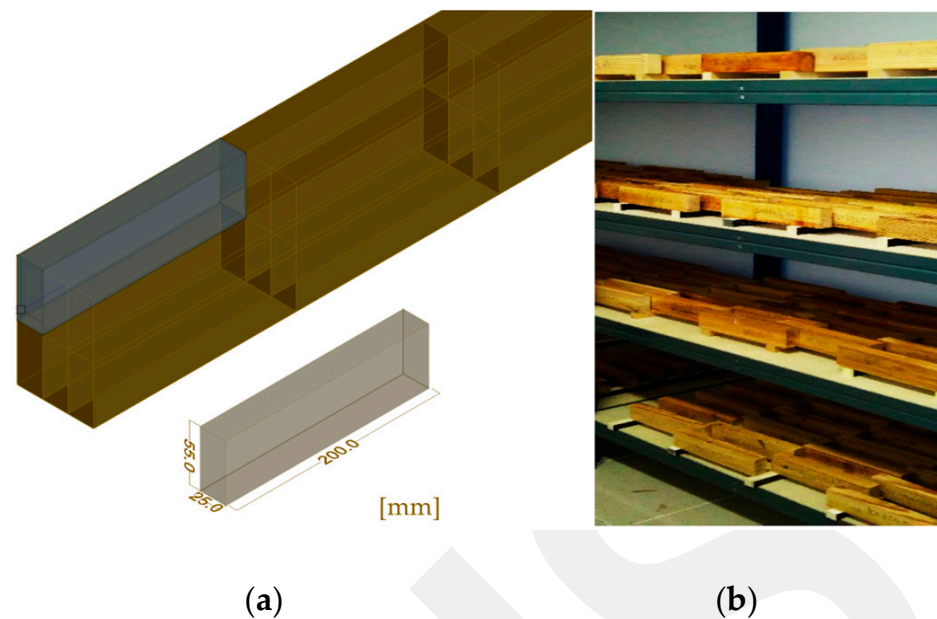


Figure 2. (a) Beam cutting and specimen geometry, and (b) conditioning of the specimens during the stabilization process.

2.3. Laboratory-Phase Needle Penetration Tests

Numerous wood defects, iron nails, and signs of biological degradation were observed on the faces of the beams. The samples' degree of deterioration was visually assessed, and they were marked as suitable or unsuitable for the needle penetration test. A cut-off criterion was used whereby more than 90% of the cross-section of the samples tested had to be free of defects. Consequently, about two-thirds of the prepared specimens were rejected prior to the SDTs (Table 1).

Table 1. Characteristics of the beams and number of specimens.

Beam Code	Dimensions (m)		Number of Specimens (25 × 55 × 200 mm)	
	Section	Length	Total	Suitable for Test
10A	0.11 × 0.14	1.52	24	13
10C	0.14 × 0.15	1.40	48	24
10E	0.15 × 0.15	1.48	48	8
10F	0.14 × 0.15	1.49	49	11
3D	0.12 × 0.13	1.50	20	12
Total			189	68

The specimens used for further testing were shown in Figure 3. Since the density of wood varies on the length of the beam, needle penetration resistance (NPR) tests were carried out on the same wood samples to obtain calibration data.

A total of six needle penetration tests were carried out transversely to each sample: three on the larger side and three on the smaller side (Figure 3). Test readings differing by more than 2 mm from the average value were excluded from the analysis. A total of 408 results were obtained from 68 samples.

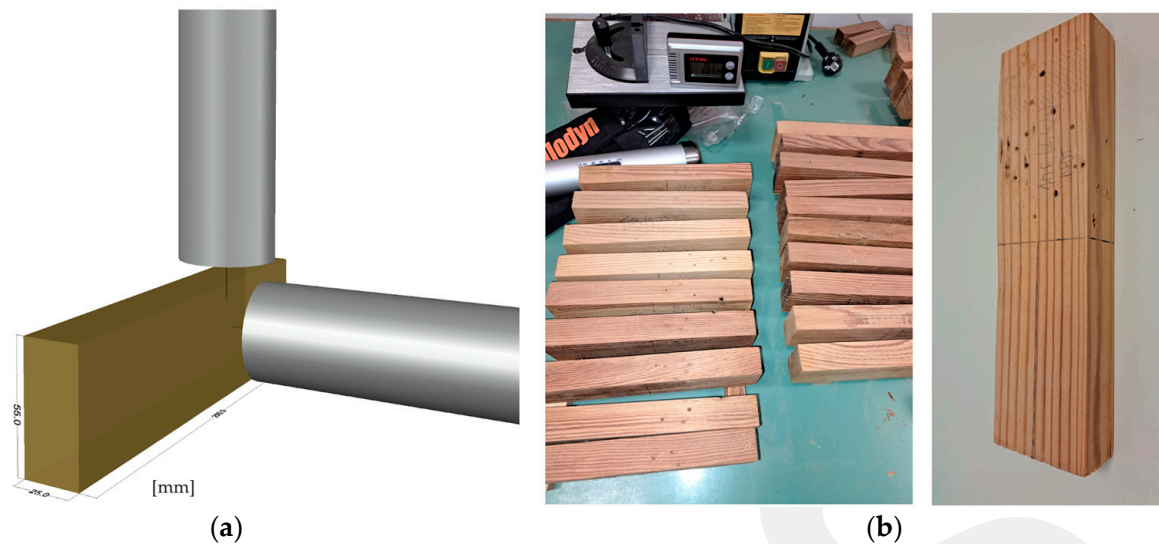


Figure 3. (a) Illustration of NPR perpendicular to the grain of *Pinus sylvestris* beams, and (b) specimens after NPR laboratory testing.

2.4. In Situ Moisture Content Determination, Needle Penetration, and Core Drilling

This task represents the central objective of this study: the estimation of density of the structural element in situ, which forms the basis for assessing the safety conditions in accordance with Eurocode5 (EN 1995-1-1: 2004) [36]. The task was carried out in two steps: (a) first, using the results of laboratory phase needle penetration and core drilling tests to establish a calibration for estimating density values, and (b) second, applying core drilling tests to measure the real density (measured density).

An extensive in situ application of the laboratory findings was carried out involving four buildings, courtesy of the company “Spybuilding”. The buildings of 18th to the 20th centuries are located in the historical center and outskirts of Lisbon, as detailed in Table 2. All the buildings were built with a masonry structure and pine woods (*Pinus* spp.).

Table 2. Characterization of the buildings where wood samples were obtained.

Building	Original Construction From	Location
A	Last quarter of the 18th century	Historical center of Lisbon
B	Middle of the 19th century	Outskirts of Lisbon
C	Last quarter of the 19th century	Historical center of Lisbon
D	The 1940s of the 20th century	Outskirts of Lisbon

The following tests were performed in situ:

- Determination of the wooden elements’ moisture contents as well as the relative humidity and temperature values of the building during the days of the inspections (Figure 4);
- Visual inspection of the geometric dimensions and conservation state of structural elements (Figure 4);
- Estimation of the density of structural elements with NPR testing in situ (Figure 4);
- Core drilling of structural elements in situ to obtain the measured density after conditioning (Figure 5).

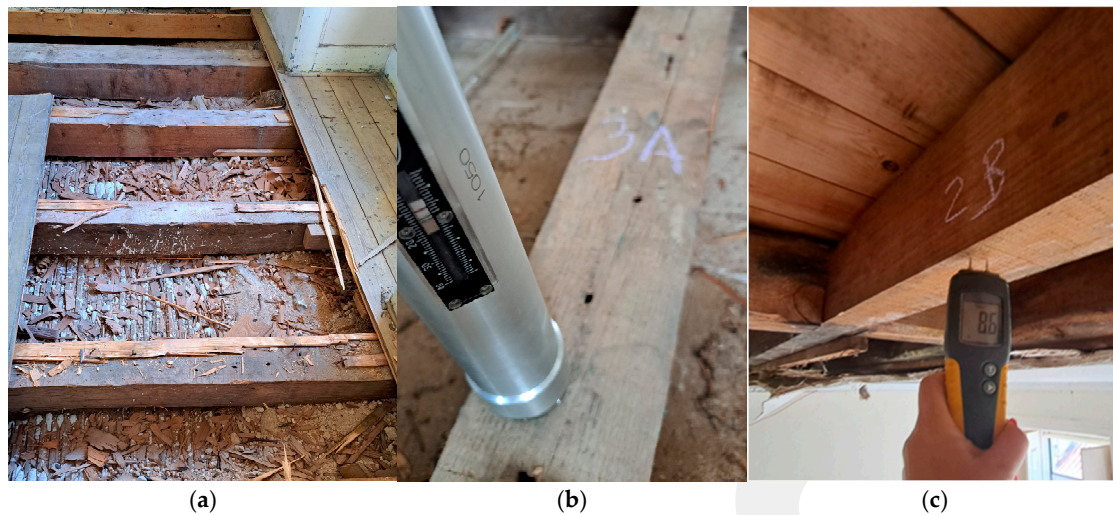


Figure 4. (a) Visual inspection of timber members; (b) needle penetration test; and (c) moisture content determination.

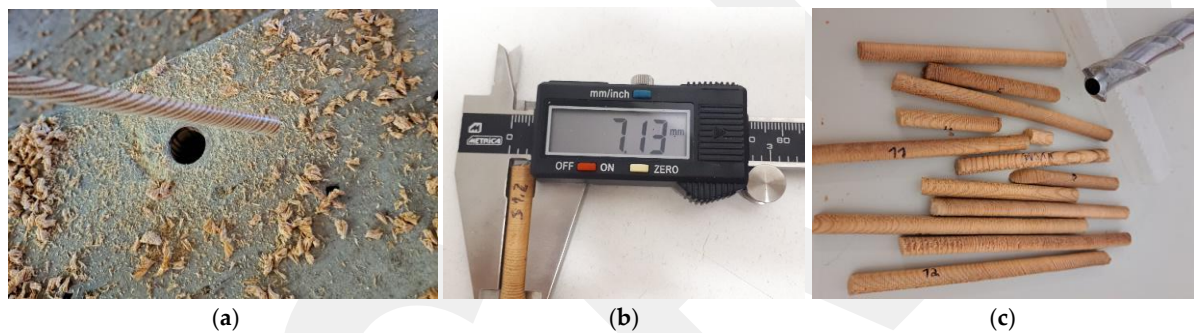


Figure 5. (a) In situ core extraction; (b) determination of the real (measured) wood density from wood cores; and (c) structure of wood cores.

A total of 2 to 5 wood cores with a diameter of 7 mm and lengths up to 120 mm were drilled from each building.

2.5. In Situ Density Estimation

The density of the wood elements was estimated using the previous correlation established after the laboratory-phase density determination and needle penetration tests (Section 3.1). Since the moisture content of the structural elements in the buildings were different from 12%, a moisture correlation of the NPR results was required. To this end, a recent moisture correlation [31] suggested for *P. sylvestris* wood was used (Equation (1)).

$$NP_{corrected} = \frac{NP_{measured}}{1 + 0.015 \times \Delta u} \quad (1)$$

In this equation, $NP_{measured}$ is the needle penetration test result (mm) and Δu (%) is the moisture content difference (%) between the in situ and reference (12%) moisture contents.

After obtaining the corrected NPR values, the correlation between the air-dry density and needle penetration (NP) was used to estimate density values. These values were later compared to the real density values calculated from core drilling measurements after air-conditioning of the cores as a sensitivity analysis. A total of 18 extracted cores were used for the density determination, with four, five, or seven readings were taken, depending on the uniformity of the wood surface and the disparity of resulting values. Core drilling

was also used to assess the decay in the tested samples because NP tests are not suitable to assess the decay in thick wood samples.

Since the wood density was measured on defect-free and small wood samples ($20 \times 20 \times 30$ mm) and reported as oven-dry values, the estimated density results were validated by comparing them with the previously reported oven-dry density values using the following equation (Equation (2)) for transformation [37]:

$$\rho_u = \rho_0 \times \frac{1 + u}{1 + 0.84 \times \rho_0 \times u} \quad (2)$$

where ρ_u is the density at moisture content u , and ρ_0 (kg/m^3) is the oven-dry density.

2.6. Statistical Tests

The t -statistics for the regression analysis were calculated using Equation (3) as follows:

$$t = \frac{r \times \sqrt{N - 2}}{\sqrt{1 - r^2}} \quad (3)$$

where r is the Pearson correlation coefficient and N is the number of samples tested.

Relative and normalized root mean squared errors (RMSEs) of the needle penetration-based density estimation model were calculated by dividing the RMSE values by the average actual density and density range, respectively.

3. Results and Discussion

3.1. Correlation Between Needle Penetration and the Air-Dry Density

For each of the 68 samples, a pair of data was obtained: average of the penetration resistance tests; air dry density. A scatter plot was constructed using these two sets of data, showing their relationship on a two-dimensional plane (Figure 6). In this graph, each blue dot represents the data for one sample. The calculation of the correlation resulted in a coefficient of determination (R^2) value of 0.76, which can be considered a reasonable or good correlation. A linear regression analysis between the needle penetration depth and wood density resulted in an R^2 of 0.76 ($r = 0.872$, $n = 68$). The relationship was statistically significant, $t(66) = 14.5$, $p < 0.0001$, indicating that penetration depth is a strong predictor of the density.

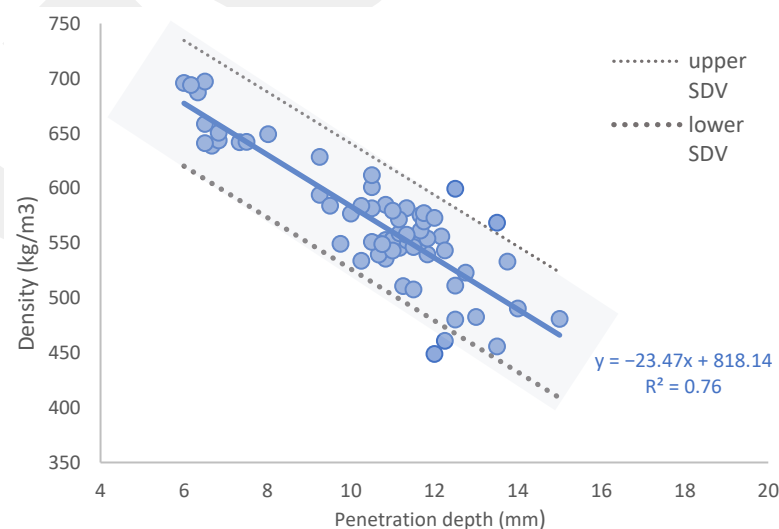


Figure 6. Results of the needle penetration test versus density along with upper and lower standard deviations (SDVs).

Previously, several authors reported varying correlations between wood density and NPR tests using Pilodyn 6J. The range of results is not surprising given the variability of wood density between different wood species as well as the variability of density in the same wood species. Various timber species were tested and correlation coefficients between the Pilodyn results and density ranged from 0.74 to 0.92, depending on the number of measurements and the species [38,39]. The authors of [34] investigated the correlation between penetration resistance using Pilodyn and the density of structural wood elements of the Scots pine (*Pinus sylvestris* L.) species obtained from an 18th century building, achieving a coefficient of determination of 0.59. The authors of [40] found good correlation coefficients (−0.73 and −0.68) between the wood density and pin penetration depth for *Pinus pinaster* standing trees. Also, the author of [41] obtained a stronger correlation ($R^2 = 0.91$) between the Pilodyn penetration depth and density of chestnut (*Castanea sativa* Mill.) wood. The authors of [39] tested in situ two king-post timber structures with a moisture content different from that of the laboratory conditions and found a moderate coefficient of determination (R^2) of 0.50, and the authors of [6] tested *Pinus sylvestris* and *Pinus pinaster* samples with 195 readings, finding a coefficient of determination (R^2) value of 0.80.

3.2. Penetration Resistance and Effect of the Moisture Content

The moisture content of wood used as structural elements in buildings is usually lower than 20% [42]. However, the moisture content in wood can vary due to the atmospheric conditions to which wood is exposed. Also, it is important to obtain the density values of wood under the in-service conditions (air-dry conditions). Thus, the determination of moisture content in wood is crucial for estimating the wood density in situ.

The results of the measured moisture contents indicated that the moisture contents of wood varied between 8.6% and 12.6% (Table 3). The wooden elements showed different moisture contents in the various locations tested in the four buildings. These values differed significantly from those under laboratory conditions (12%). Therefore, readings of needle penetration into wood under real environmental conditions had to be corrected to ensure a correct density comparison with the reference values. There are some previous studies that present correlations between the density and moisture content for different types of wood species, such as *Pinus sylvestris*, *Pinus pinaster*, *Pinus radiata*, *Pinus nigra*, *Picea abies*, etc. [27–29]. This study used the moisture correlation of Equation (1), presented by [31] for the Scots pine wood species, for correcting the NP to a moisture content of 12% [31] (Table 3).

Table 3. Results of penetration readings and core drilling readings. Comparison of wood density.

Identification	Moisture Content (u) In Situ (%)	Number of Readings In Situ	NPR Testing Penetration Depth (mm)		Wood Density (kg/m³)		
			In Situ	Corrected to 12% u * by Equation (1)	Density Estimated by Equation (4)	Core Drilling (Measured Density at u = 12%)	Difference Between Estimated and Measured Density (%)
A—building from the 18th century’s last quarter—historical center of Lisbon							
A1	10.1	5	12.8 ± 0.8	13.2	509	545	6.6
A2	10.3	5	13.3 ± 0.8	13.6	498	481	3.5
A3	9.8	5	12.7 ± 1.0	13.1	510	559	8.8
A4	11.3	5	12.0 ± 0.5	12.1	534	572	6.7
A5	10.8	5	13.5 ± 2.3	13.7	495	477	3.9
A6	11.2	5	13.2 ± 0.3	13.4	505	487	3.6

Table 3. Cont.

Identification	Moisture Content (u) In Situ (%)	Number of Readings In Situ	NPR Testing Penetration Depth (mm)		Wood Density (kg/m ³)		
			In Situ	Corrected to 12% u * by Equation (1)	Density Estimated by Equation (4)	Core Drilling (Measured Density at u = 12%)	Difference Between Estimated and Measured Density (%)
B—building from the mid-19th century—outskirts of Lisbon							
B1	12.1	5	12.5 ± 0.5	12.5	525	541	2.9
B2	11.1	5	13.3 ± 0.5	13.5	502	499	0.5
C—building from the 19th century’s last quarter—historical center of Lisbon							
C1	9.0	5	17.2 ± 1.9	18.0	395	387	2.2
C2	8.6	7	11.1 ± 0.9	11.7	544	560	2.9
C3	10.8	7	13.5 ± 1.5	13.7	495	470	5.4
C4	10.4	5	10.7 ± 1.0	11.0	561	645	13.0
D—building from the 1940s of the 20th century—outskirts of Lisbon							
D1	12.6	4	13.2 ± 1.1	13.1	Ne **	421	-
D2	11.7	4	11.3 ± 0.5	11.4	552	558	1.1
D3	12.5	4	12.8 ± 0.8	12.7	520	511	1.8
D4	12.3	4	16.0 ± 1.0	15.9	444	426	4.3
D5	11.4	4	13.5 ± 1.3	13.6	498	509	2.1
D6	12.1	4	12.8 ± 1.2	12.8	518	480	8.0
Average					506	512	4.6
Std					38	61	3.2
Relative RMSE (%)					5.6		
Normalized RMSE (%)					11.7		

* Values were corrected to a moisture content (u) of 12%, compared to those of the measurement on site. ** Not estimated (ne) due to the presence of extensive resin pockets.

3.3. Estimation of the Wood Density In Situ

Despite the limitations of carrying out a superficial test, Pilodyn is an easy-to-use device with which a high number of readings can be obtained quickly. This feature makes it possible to discard the highest and the lowest values and thus obtain a very reliable average value.

The wood density was estimated using the indirect needle penetration method based on the regression equation derived from the laboratory tests, as follows (Equation (4)):

$$\rho_{i, in-situ} = -23.47 \times NP_{i, corrected} + 818.14 \quad (4)$$

where

- $\rho_{i, in-situ}$ is the estimated density (kg/m³) of reading i ;
- $NP_{i, corrected}$ is the reading i of the needle penetration tests, corrected by Equation (1) (mm).

Equation (5), which results from integrating Equation (1) with Equation (4), provides an estimate of the density of an in situ wood element at $u = 12\%$, based on an average of the in situ NP readings and the water content measured on site during the tests:

$$\rho_{i, in-situ} = -\frac{23.47 \times NP_{i, in-situ}}{1 + 0.015 \times \Delta u} + 818.14 \quad (5)$$

where

- $\rho_{i, in-situ}$ is the estimated density (kg/m³) of in situ reading i ;
- $NP_{i, in-situ}$ is the in situ reading i of the needle penetration tests (mm);
- Δu (%) is the moisture content difference (%) between the in situ and reference (12%) moisture contents.

Table 3 presents the results for the penetration depth (NP) obtained on site and corrected to a reference (12%) moisture content (u) and the number of readings, and the estimated and real wood densities. The difference refers to the estimated density versus the

real (measured) density. The results showed that the differences between the measured and the estimated density values were between 0.5% and 13%, with an average value of 4.6%. The average estimated air-dry density was 512 kg/m^3 , which was close to the average real density (506 kg/m^3) (Table 3). The density variations between the wood samples were expected and attributed to the differences in growing conditions of the tree that affect the latewood and early wood ratio and thus the density of wood [4].

A good correlation was observed between the measured and estimated density values, which can be visualized in Figure 7. The linear regression analysis between the estimated and actual density values resulted in a very high R^2 of 0.997. The relationship was also statistically significant $t(15) = 70.6$, $p < 0.000001$, showing a very strong correlation between the two values.

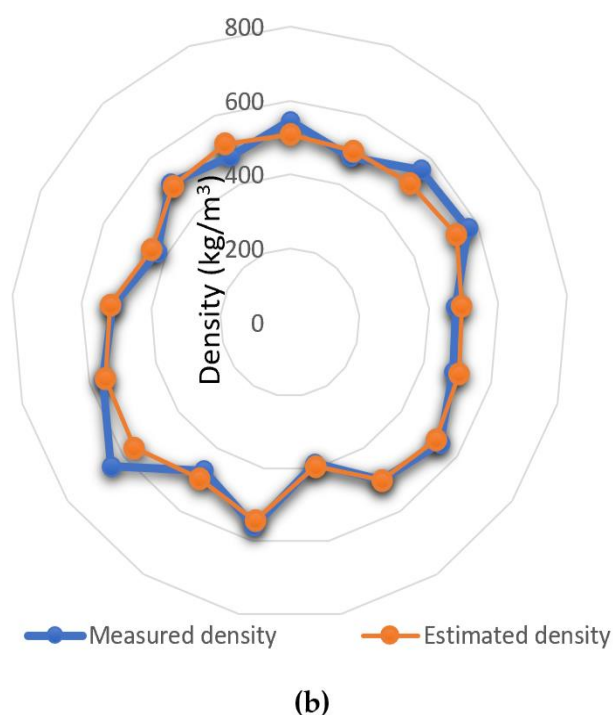
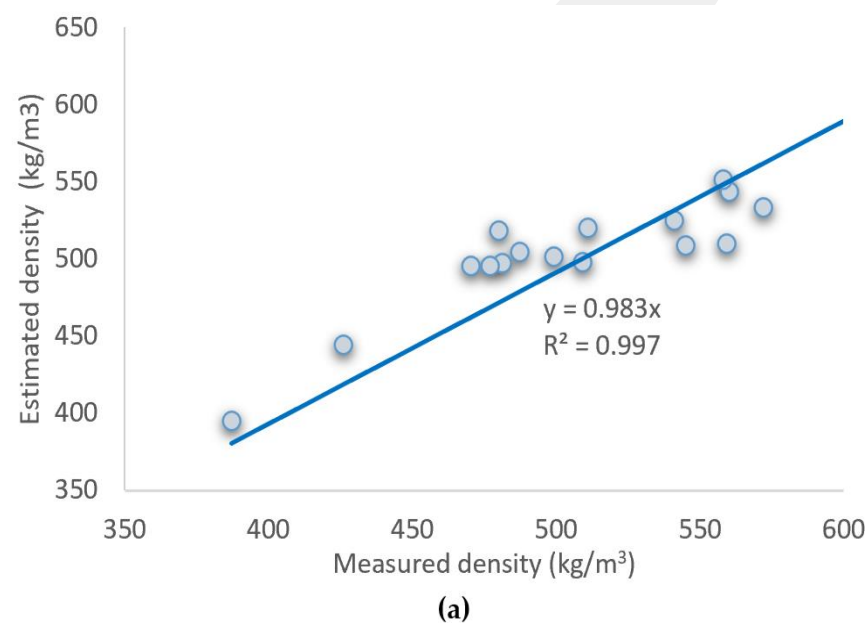


Figure 7. Relationship between the density estimated by penetration resistance tests and measured (real) density in kg/m^3 (a) and a comparison of the real and estimated density values (b).

The estimated as well as measured densities of *Pinus sylvestris* wood corresponded to an oven-dry density of 480 kg/m³ (Figure 8), which agrees with previous publications [43–45] for the wood species, indicating the precision of the in situ Pilodyn and moisture content tests.

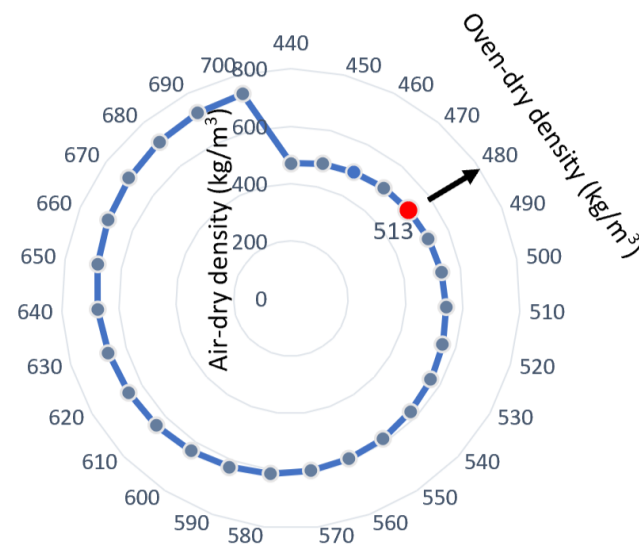


Figure 8. Relationship between the estimated air-dry density (red) and oven-dry density of *Pinus sylvestris* wood (corresponding value in the outer circle) in kg/m³.

The findings indicate that the wood structures in the heritage buildings of Lisbon are well-preserved after hundreds of years of service, possibly due to the low moisture content of the wood elements.

4. Conclusions

The present study investigates the in-service density assessment of timber structural elements through semi-destructive testing methods that preserve the integrity of the wooden elements. This research encompassed both controlled laboratory experiments and on-site field evaluations, and its main innovation lies in the combined use of moisture content measurements and needle penetration testing. This approach enables the density of wood in old buildings to be assessed using the Pilodyn® device at varying moisture contents. It also demonstrates the effectiveness of the device as a semi-destructive testing tool for wood in service, particularly for indirectly estimating the wood density in heritage buildings.

The results of the needle penetration test showed a good correlation between the wood density and needle penetration depth, with a coefficient of determination (R^2) value of 0.76. The sensitivity analysis, performed by measuring the density of wood cores extracted from structural elements in service followed by a comparison of the density estimated by NPR tests, revealed a strong correlation with a coefficient of determination of 0.99.

It is concluded that the needle penetration resistance test is a reliable and practical method for estimating the density of wood structures in service, making it especially valuable for heritage buildings.

Author Contributions: Conceptualization, D.F.H.; methodology, D.F.H.; formal analysis, D.F.H.; investigation, D.F.H.; resources, D.F.H.; writing—original draft preparation, D.F.H.; writing—review and editing, D.F.H., A.U.S., and M.d.G.G.; visualization, M.d.G.G.; funding acquisition, D.F.H. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the financial support from the Foundation for Science and Technology (FCT) through the project UIDB/04625/2025 of the research unit CERIS and Instituto Politécnico de Lisboa (IPL) for financial support to the WOODINSITU project (ref. IPL/2016/WOODINSITU) and to the TEC-TIMBER project (IPL/2019/TEC-TIMBER_ISEL).

Data Availability Statement: The data are contained within the article.

Acknowledgments: The authors thank Spybuilding-Inspecção de Edifícios, Lda. for supporting the application of laboratory findings to real buildings and Marcos Marques, research project fellow, whose collaboration was unsurpassed.

Conflicts of Interest: The authors declare no conflicts of interest.

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