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NONDESTRUCTIVE TESTING USED ON TIMBER IN SPAIN: A LITERATURE REVIEW

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ABSTRACT

Nondestructive testing (NDT) includes several highly efficient techniques for the estimation of the physical and mechanical properties of structural timber. Apart from visual grading, scientific research using Nondestructive testing on timber has been used in Spain since the 1990s. Nondestructive testing can be used for two different purposes: timber grading and the assessment of existing timber structures. The most common devices used in Spain are portable ones based on ultrasound, stress waves, vibration and probing techniques. Many statistical linear models for estimating the mechanical properties of new sawn timber and timber from existing structures have been proposed. Furthermore, several factors that affect Nondestructive testing measurements have been studied (moisture content, temperature, specimen dimensions, sensors position-grain angle, among others) and adjustment factors have also been proposed. Species have been characterized for visual grading standards from the 1980s to date. The large number of research works using different species, devices and procedures shows the need of homogenization and standardization of Nondestructive testing use. This paper presents a review of research works using Nondestructive testing on timber in Spain, in order to add to knowledge, elucidate the concepts to unify Nondestructive testing used and promote research group collaboration in the near future.

Keywords: Acoustic techniques, nondestrucyive testing, stress waves, structural timber, ultrasound waves, vibration techniques.

INTRODUCTION

Scientific research into the determination of timber mechanical properties began in Spain in the 1960s, in the INIA Structural Timber Laboratory (Figure 1a). Arriaga *et al.* (1992) published the first scientific research work using Nondestructive Testing (NDT) on timber in Spain. The Steinkamp BP-V (BPV), a portable ultrasound device with exponential tip 50 kHz sensors, was used on 34 pieces from existing structures to estimate their mechanical properties with determination coefficients (R^2) between the modulus of elasticity (MOE) and the dynamic modulus of elasticity (Edyn) of 37 % (Figure 1b). Martínez (1992) used the same NDT device on structural maritime pine timber (40 mm x 100 mm and 50 mm x 150 mm) in his PhD thesis. Bucur *et al.* (1993) presented the first SCI JCR publication in Spain of NDT on timber using the BPV and X-ray for fungal decay detection in pine and European beech. Several other works were presented with a focus on detecting decay and defects using ultrasound waves (Palaia *et al.* 1993, Galvañ *et al.* 1994, Martín 1994, Troya and Navarrete 1994). Rodríguez-Liñán and Rubio (1995) and Rubio (1997) estimated MOE and bending strength (MOR)

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of new Scots pine timber, timber from existing structures and small clear specimens using the BPV with a R^2 from 36 % to 44 % for MOE and MOR, respectively. Pedras *et al.* (1997) estimated MOE from velocity, with a R^2 of 81 % in small clear sweet chestnut specimens. Palaia *et al.* (2000) proposed models for density (ρ) estimation from needle penetration resistance (NPR) depth using the Pilodyn with a R^2 of 80 % using small clear specimens of Scots, maritime and Caribbean pitch pine. Riesco (2001) used BPV velocity to estimate the MOE of small clear specimens of European oak with a 40 % R^2. At the end of the 1990s an automatic bending classification machine, the Cook Bolinders (SG-AF Tecmach Ltd., St. Albans, UK), arrived in the INIA Structural Timber Laboratory (Figure 1c). Hermoso (2001) reported the settings used to classify Spanish Scots pine with this machine, and Conde (2003) presented the settings for Salzmann pine. Furthermore, both doctoral theses also estimated structural timber MOE and MOR from ultrasound wave velocity using the Sylvatest (Syl) portable device combined with visual grading parameters.

Acoustic techniques (ultrasound and stress waves)

Esteban (2003) used BPV and Sylvatest Duo (SylDuo) measurements combined with visual parameters to estimate the mechanical properties of Scots and maritime pine from existing structures. Hermoso *et al.* (2003) compared grading results using the Syl and Cook Bolinders, obtaining a lower rejection percentage with the latter for Scots and Salzmann pine. Arriaga *et al.* (2006) reported a R^2 of 73 % when estimating MOE from SylDuo velocity in missanda. Capuz *et al.* (2007) estimated a C18 strength class based on in-situ SylDuo measurements in the timber structured historic building “Lonja de Mercaderes” in Valencia. Hermoso *et al.* (2007) studied Salzmann pine round small-diameter timber, estimating MOE from Edyn with a 68 % R^2. Íñiguez-González (2007) used ultrasound on large cross-section radiata, Scots and Salzmann pine timber (150 mm x 200 mm, 200 mm x 250 mm) to estimate their properties. Palaia *et al.* (2008) presented a procedure for the assessment of timber structures using several NDT techniques, testing them on Scots pine from existing structures. Basterra *et al.* (2009) evaluated historic buildings in “Chinchón Plaza Mayor” using ultrasound and probing techniques. Carballo *et al.* (2009a), Carballo *et al.* (2009b) presented a review of 30 years of NDT, together with an estimation of maritime pine MOE using the SylDuo and MicroSecond Timer (MST) velocity with a R^2 of 55 % and 70 % with the Edyn. In the case of MOR, a R^2 of 39 % was found when a knottiness parameter was included. Esteban *et al.* (2009) estimated MOE and MOR by stress waves and probing methods using the Íñiguez-González (2007) models, and assigned a strength class in the assessment of the Valsaín sawmill historic building (Figure 1d). Atienza-Conejo (2012) used pulse-echo ultrasound to detect xylophage insect attack in timber ships. Casado *et al.* (2012) estimated the MOE of black poplar timber by combining SylDuo velocity and visual parameters with a R^2 of 68 %. Montón (2012) tested Catalonian radiata pine, estimating its properties with ultrasound and stress waves. Vega *et al.* (2012) estimated the mechanical properties of sweet chestnut using the Sylvatest Trio (SylTrio) and MST, obtaining a R^2 of 70 % using Edyn or velocity and density. However, MOR was estimated with a R^2 of 27 % even when a knottiness parameter was included. Merlo *et al.* (2014) used the IML Micro Hammer (IML MH) device (IML, Wiesloch, Germany) on standing maritime pine trees estimating the MOE of sawn boards from these trees with a R^2 of 55 %. Vázquez *et al.* (2015) used 13 polyhedral small clear specimens of sweet chestnut to determine Young’s moduli, shear moduli and Poisson’s ratios by ultrasound with 1 MHz sensors, finding a good correlation with MOE of structural timber. Vilches *et al.* (2015) assigned strength classes C14 and C18 to Scots pine beams from an existing structure by stress waves using the Íñiguez-González (2007) models. Abián and Segura (2016) estimated the residual capacity of fire-damaged Scots pine timber from existing structures using the ultrasound wave method. Llana (2016) used the USLab device with 45 kHz sensors to estimate MOE from Edyn with a R^2 of 90 %. Crespo *et al.* (2017) tested small clear specimens of southern blue gum with 1 MHz ultrasound sensors to obtain their elastic values. Morales-Conde and Machado (2017) used PUNDITplus (Proceq, Schwerzenbach, Switzerland) with 54 kHz sensors and MST on 30 clear wood pieces of maritime pine to estimate MOE from Edyn. Higher R^2 (91 %) combining MST measurements at different depths than using PUNDIT (71 %) was found. Hillig *et al.* (2018) used SylDuo, USLab and MST devices to study wood-polymer-composites in the Universidad Politécnica de Madrid Timber Laboratory. Osuna-Sequera *et al.* (2019a) studied several criteria to determine the cross-section in existing timber structures to estimate MOE from Edyn. Vega *et al.* (2019a) estimated MOE of 216 dry sweet chestnut small-diameter logs using MST velocity and Edyn with R^2 of 64 % and 67 %, respectively and a grading system was designed based on MST velocity.

Figure 1: Spanish scientific timber research facts: a) INIA Structural Timber Laboratory in the1960s and 1970s. b) Arriaga *et al.* (1992) ultrasound measurements. c) Cook Bolinders, INIA Structural Timber Laboratory. d) Valsaín sawmill historic building.

Vibration techniques

Arriaga *et al.* (2005a) published the first scientific research work done in Spain with vibration technique to grade 75 radiata pine specimens using the Portable Lumber Grader (PLG). Broto *et al.* (2007) tested 211 specimens of Scots pine using the Mechanical Timber Grader (MTG), finding that 73 % of the specimens were undergraded and 7 % were overgraded. Íñiguez-González (2007) applied the PLG to large cross-timber of radiata, Scots and Salzmann pine, obtaining similar R^2 for MOE estimation from vibration and ultrasound velocity. Santaclara *et al.* (2009) tested 200 sawn timber pieces of Douglas fir containing a large amount of juvenile wood using PLG, and they found a better R^2 in MOE estimation which combined velocity and knottiness parameters rather than velocity and density. Villanueva (2009) tested Spanish juniper round wood by longitudinal vibration, obtaining a R^2 of 43 % when estimating MOE by combining Edyn and conicity parameters. Rojas *et al.* (2011) used a microphone to record the natural frequencies of veneer samples for species identification. Santaclara and Merlo (2011) used the Hitman Director HM200 (HM200) on 162 logs of maritime pine before testing sawn timber from them. A R^2 of 73 % was reported when estimating sawn timber MOE from logs using the Edyn. Arriaga *et al.* (2012) published the preliminary grading settings for European standard EN 14081-2 (2010) of PLG for Spanish radiata, Scots and Salzmann pine, but were not implemented in the Spanish industry. Montero (2013) tested Scots pine sawn timber with several NDT devices, concluding that PLG results are the best mechanical property estimators. Vega (2013) compared sweet chestnut results from two different vibration devices, the PLG with a microphone and the HM200 with a contact accelerometer, finding better mechanical properties estimation with the PLG measurements. Arriaga *et al.* (2014) estimated radiata pine mechanical properties based on longitudinal and transversal vibration with similar accuracy. Llana (2016) used the PLG with a microphone and the MTG with a contact accelerometer to estimate MOE with a 91 % R^2 and MOR at 70 % using the Edyn, and found no significant differences between the results of both devices. Osuna-Sequera (2017) tested 11 m long large cross-section Salzmann pine beams from an 18th century timber structure using the PLG and estimating MOE using the Edyn with an 80 % R^2. Not only restraint-free isolated specimens were analyzed using the vibration technique, as multiple contact accelerometers were also used to evaluate timber structures. Baño *et al.* (2011) studied resonance risk in Scots pine timber footbridges, while Castro-Triguero *et al.* (2017) evaluated a 125 m length timber footbridge and Arce-Blanco (2017) tested Salzmann pine plank timber arches. Currently, the first research experience on vibration testing of light frame timber floors in Spain is carried out by the Timber Structures and Wood Technology Research Group of the University of Valladolid, after developing their own accelerometers (Villacorta-Calvo *et al.* 2019). Furthermore, scientists from the previous research group patented a transversal vibration system using several microphone receptors for the evaluation of existing timber structures (Gutiérrez-Sánchez *et al.* 2019).

Probing techniques

Probing methods (needle and drill penetration resistance, screw and nail withdrawal resistance) are mainly used to estimate density in existing timber structures. Palaia *et al.* (2000) used the Pilodyn to estimate the density of small clear specimens of Scots, maritime and Caribbean pitch pine. Casado *et al.* (2005) predicted density using the Screw Withdrawal Resistance Meter (SWRM) on 39 Scots pine joists from an existing structure. Bobadilla *et al.* (2007) estimated density using the Pilodyn and SWRM on 395 large cross-section specimens of radiata, Scots and Salzmann pine with a R^2 of 35 % and 49 %, respectively. Íñiguez-González *et al.* (2010) proposed estimation density models for large cross-section radiata, Scots, Salzmann and maritime pine, finding a better R^2 with probing techniques than was the case with ultrasound waves. Montón (2012) introduced core drilling technique for density estimation in Spain, obtaining a higher R^2 than was the case with the Pilodyn or SWRM in radiata pine. Bobadilla *et al.* (2013) presented the definitive prototype of the RML Wood Extractor (GICM-UPM, Madrid, Spain) in a NDT wood conference in Madison, WI, USA. 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. The UNE 41809 (2014) was published for use of the penetrometer in wood elements to diagnose existing buildings. Íñiguez-González *et al.* (2015a) compared density estimation by using the Pilodyn, SWRM and core drilling, obtaining the highest R^2 with the latter. Bobadilla *et al.* (2018) estimated density by core drilling technique on small clear specimens of 10 species with a R^2 of 98 %. Llana *et al.* (2018a) presented a comparison between the Pilodyn, Wood Pecker, SWRM, core drill and RML WoodEx for density estimation of Norway spruce from an existing timber structure, obtaining a better R^2 with the core drill and RML WoodEx. The drilling resistance technique using Resistograph and IML Resi devices was used to evaluate timber structures (Capuz *et al.* 2007, Basterra *et al.* 2009, Touza 2009, Montoya-Morguí 2010, González-Sanz 2012, Lozano *et al.* 2013, Abián and Segura 2016) and also for density estimation (Mariño *et al.* 2002, Casado *et al.* 2005, Vilches and Correal 2009, Soto-Martínez 2010, Acuña *et al.* 2011, Morales-Conde *et al.* 2014, Camacho-Valero 2017).

Other NDT techniques

Neuronal networks using data from NDT were studied for timber grading (Mier 2001, García-Esteban *et al.* 2009, García-de-Ceca *et al.* 2013, García-Iruela *et al.* 2016, Villasante *et al.* 2019). Mariño *et al.* (2010) studied the influence of pith distance on velocity using acoustic tomography. Rodríguez-Abad *et al.* (2011) used ground-penetrating radar (GPR) on 22 maritime pine joists to estimate MC and Martínez-Sala *et al.* (2013) studied the differences between longitudinal and transversal GPR measurements. Morales-Conde *et al.* (2013) used infrared thermography (IRT) to detect MC differences. Oliver and Abián (2013) developed a sensor to monitor timber structures for termites using light emission and fungi risk by moisture content estimation. Sánchez-Beitia *et al.* (2015) presented the application of Hole-Drilling technique on small clear specimens of radiata pine for stress quantification, and Crespo-de-Antonio *et al.* (2016) used it to assess two existing timber structures. López *et al.* (2018) estimated wood density from the variation of surface temperature when specimens are cooled using IRT. Ruano *et al.* (2019) determined the ratio of juvenile wood to mature wood using near infrared-hyperspectral imaging.

Adjustment factors

The results of NDT are affected by several factors: moisture content (MC), temperature (T), specimen dimensions, sensor positioning and grain angle and timber-sensor coupling, to mention just a few. Íñiguez-González *et al.* (2015b) published a compilation of NDT adjustment factors from the national and international literature. Rodríguez-Liñán and Rubio (1995), Rodríguez-Liñán and Rubio (2000) and Palaia *et al.* (2000) published some of the first Spanish studies of MC influence on NDT measurements using the BPV. Regarding T, Llana *et al.* (2014) reported the influence of T on NDT, showing a clear linear tendency below 0ºC and no significant tendency above 0ºC for dry Scots pine small clear specimens. The length effect was found several times in ultrasound velocity using the SylDuo (Arriaga *et al.* 2006, Acuña *et al.* 2007, Íñiguez-González *et al.* 2007a, Llana *et al.* 2013) and an adjustment procedure was proposed (Llana *et al.* 2016). The influence of dimension was also reported on the velocity obtained by vibration using PLG (Carballo *et al.* 2007, Casado *et al.* 2010). Concerning sensor position with respect to the grain, Rodríguez-Liñán and Rubio (1995) observed a ratio between face to face and end to end velocity (V_f/V_0) of 1,19 and between perpendicular and longitudinal velocity (V_{90}/V_0) of 2,9. Esteban (2003) found a V_{90}/V_0 of 4 and Íñiguez-González *et al.* (2009) found this to stand at from 2,5 to 3. Several authors proposed adjustments depending on the angle respect to the grain (Acuña *et al.* 2007, Arriaga *et al.* 2009, Balmori *et al.* 2016). Arriaga *et al.* (2017a) found differences between the velocity obtained in end-to-end measurements and surface or crossed measurements equal to or less than 4,4 % on average.

Visual grading

Visual grading is the oldest nondestructive timber evaluation technique. The first Spanish visual grading standard UNE 56525 (1972) was published in December 1972 for structural timber. Seven visual grades were defined (Extra/100, I/80, II/70, III/60, IV/50, V/40 y VI). Argüelles and Arriaga (1986) published a visual grading proposal based on a British standard, with four visual grades for sawn timber (75, 65, 50 and 40) and three for glulam lamellas (LA, LB and LC). A new visual grading standard UNE 56544 (1997) was first published in 1997, first covering softwood and hardwood species (radiata, Scots and maritime pine, black poplar and southern blue gum). Two years later Salzmann pine was also included and afterwards black poplar was excluded. In 2007 a specific standard only for hardwoods was published as UNE 56546 (2007), and the current version of this standard from 2013 is applied to southern blue gum and sweet chestnut, while UNE 56544 (2011) is now only for softwoods. Furthermore, UNE 56547 (2018) is a visual grading standard for Scots and Salzmann pinewood overhead poles. Nowadays national visual grading standards should follow the minimum requirements established by European standard EN 14081-1 (2016). Furthermore, in order to homogenize the national visual grades in all European countries, EN 1912 (2012) related national visual grades with the strength classes according to EN 338 (2016). Concentrated Knot Diameter Ratio (CKDR) is a visual parameter used frequently in combination with NDT ultrasound and vibration results. CKDR includes the influence of knots as the main defect in prediction models, improving the estimation of MOR. This parameter has often been used in Spanish research works, mainly for the assessment of existing structures.

Furthermore, the first research experience of NDT evaluation (using most of the techniques previously cited) of recovered wood from deconstruction and demolition for reuse and recycling purposes is being gained by the Timber Construction Research Group of the Universidad Politécnica de Madrid (Íñiguez-González *et al.* 2019).

The main goal of this paper is to present the history of wood NDT used in Spain and its main milestones with three objectives. (1) To allow different Spanish and international research groups to have a better knowledge of these works. (2) To elucidate concepts to unify NDT used on timber and future standardization procedures. (3) To promote research group cooperation and exchange activities.

Summary of species and devices used in the literature

Species

Structural sawn timber, round wood and small clear specimens from several Spanish-grown species tested with NDT methods were found in the literature: radiata pine (*Pinus radiata* D. Don), Scots pine (*Pinus sylvestris* L.), Salzmann pine (*Pinus nigra* Arnold ssp. *salzmannii* (Dunal) Franco), Corsican pine (*Pinus nigra* Arnold ssp. *laricio* (Poir.) Maire), maritime pine (*Pinus pinaster* Ait. ssp. *mesogeensis* Fieschi & Gaussen and *Pinus pinaster* Ait. ssp. *atlantica* H. de Vill.), Aleppo pine (*Pinus halepensis* Mill.), black poplar (*Populus x euramericana* (Dode) Guinier), southern blue gum (*Eucalyptus globulus* Labill.), sweet chestnut (*Castanea sativa* Mill.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), silver fir (*Abies alba* Mill.), robinia (*Robinia pseudoacacia* L.), Japanese larch (*Larix kaempferi* (Lamb.) Carr.), Spanish juniper (*Juniperus thurifera* L.), European beech (*Fagus sylvatica* L.), European oak (*Quercus robur* L.) and Paulownia (*Paulownia elongata* S.Y.Hu). Some other abroad-grown species but sawn and commercialized in Spain for structural purposes were also found in the literature: missanda (*Erythrophleum ivorense* A. Chev. and *Erythrophleum suaveolens* (Guill. & Perr.) Brenan), iroko (*Milicia excelsa* (Welw.) C. C. Berg and *Milicia regia* (A. Chev.) C. C. Berg), Norway spruce (*Picea abies* (L.) Karst.), southern pine (*Pinus tadea* L.), American pitch pine (*Pinus pallustris* Mill.), Caribbean pitch pine (*Pinus caribaea* Morelet) and western red cedar (*Thuja plicata* Donn.).

The NDT devices used in Spain are usually portable, and the most common ones cited in the literature are:

Ultrasound and stress wave devices

Ultrasound and stress wave time-of-flight (ToF) is recorded. The most common devices are: (1) The Steinkamp BP-V (Ultratest, Achim, Germany) ultrasound device (600 V output power) equipped with 50 kHz exponential tip sensors (Figure 2a), (2) The Sylvatest Duo (220-250 V output power) and the Trio (CBS-CBT, Lausanne, Switzerland) instrument equipped with conical 22 kHz sensors (Figure 2b, Figure 2c), (3) The USLab (Agricef, Campinas, Brazil) ultrasound device (700 V output power and 0,1 μs resolution) which can be used with different sensors from 20 to 90 kHz (Figure 2e), (4) The MicroSecond Timer (Fakopp, Sopron, Hungary) an impact stress wave device (Figure 2d). Velocity is calculated by dividing length over ToF.

Figure 2: NDT devices: a) Steinkamp BP-V. b) Sylvatest Duo. c) Sylvatest Trio. d) MicroSecond Timer. e) USLab. f) PLG. g) Hitman HM 200 (courtesy of Dr. Abel Vega). h) MTG.

Vibration devices

Natural frequency data is recorded after inducing vibration by hammer impact. The most common devices found in the literature are: (1) The Portable Lumber Grader PLG (Fakopp, Sopron, Hungary) equipped with a microphone that is placed in front of one end (Figure 2f), (2) The Hitman Director HM 200 (Fibre-gen, Christchurch, New Zealand) equipped with a contact accelerometer (Figure 2g), (3) The Mechanical Timber Grader MTG 960 (Brookhuis, Enschede, Netherlands) equipped with a contact accelerometer (Figure 2h). Velocity from the first mode of natural frequency is calculated as the product of two times length and frequency.

Probing devices

The most common probing devices used in Spain for density estimation and structural inspections found in the literature review are: (1) The Pilodyn 6 J Forest (Proceq, Schwerzenbach, Switzerland) (Figure 3a). This consists of a calibrated spring that releases a 2,5 mm diameter steel needle with a constant energy of 6 J. NPR depth of this needle into the timber is measured in mm. (2) The Wood Pecker (DRC, Ancona, Italy) (Figure 3b). This modified sclerometer inserts a 2,5 mm diameter steel needle by striking several times with constant energy. NPR depth is measured in mm after each strike. (3) The Screw Withdrawal Resistance Meter SWRM (Fakopp, Sopron, Hungary) (Figure 3c). SWR force is measured in kN when a standard screw is pulled out. (4) Commercial core bits with different external diameters, usually from 10 to 22 mm (Figure 3d). The mass and volume of the cylindrical extracted core are measured. (5) The RML Wood Extractor (RML WoodEx) (GICM-UPM, Madrid, Spain) coupled to a commercial drill (Figure 3e). This Spanish design was patented in 2013 (Martínez and Bobadilla 2013) using drilling chips extraction technique. A bit is drilled to a standard depth in wood specimens (so the hollow volume is known) vacuum collecting all of the chips produced during drilling in a paper filter bag. Density is estimated from the mass of chips and volume of the hollow. (6) The Resistograph (RinnTech, Heidelberg, Germany) is a drilling resistance tool where relative resistance is measured against the introduction of a small diameter drill at a constant speed (Figure 3f). (7) The IML Resi (IML, Wiesloch, Germany) uses drilling resistance technique in a similar way to the Resistograph. There are several models, and Figure 3g shows the F400-S. Probing measurements should be taken while avoiding areas close to the pith and other singularities such as knots and resin pockets, etc.

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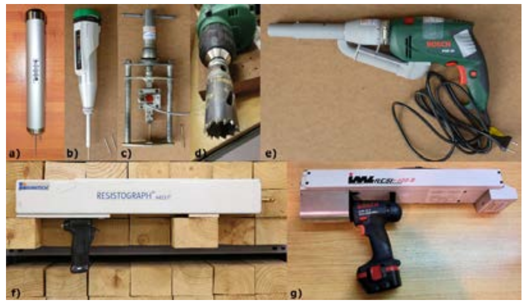

Figure 3: Probing devices: a) Pilodyn 6J Forest. b) Wood Pecker. c) SWRM. d) Core bit. e) RML WoodEx. f) Resistograph (courtesy of Dr. Joaquín Montón). g) IML Resi F400-S.

RESULTS AND DISCUSSION

Acoustic techniques (ultrasound and stress waves) for property estimation

Velocity is calculated from ToF by dividing length over ToF. The dynamic modulus of elasticity (Edyn) is calculated as the product of density and square velocity. Several authors have presented mechanical properties estimation models using velocity and Edyn (Table 1).

Table 1: Mechanical properties estimation models by acoustic techniques.

Device	MOE and MOR models (MPa)	R^2 (%)	Species/product	Reference
BPV	MOEloc=1828+0,7777*Edyn	53	Maritime p.	[7]
BPV	MOE=-20802+6,3547*V [1,2]	98	Scots p. [3]	[8]
	MOR=-61,58+0,0291*V [1,2]	70		
BPV	MOE=-2332+1,2953*V [1,2]	81	Sweet chestnut	[9]
BPV	MOE=2075+0,1569*Edyn [1,2]	60	Scots p.	[10]
	MOR=-7,31+0,0169*V [1,2]	66		
Syl	MOR=-5,50+0,0035*Edyn	38	Scots p.	[11]
Syl	MOE=$(-11+0,0235*V)^2$	52	Salzmann p.	[12]
	MOR=-114,47+0,0334*V	40		
Syl	MOEloc=$-1130+0,0005*V^2$	51	Salzmann p.	[13]
Syl	MOE=3060+0,4201*Edyn	40	Scots, maritime p. [3]	[14]
BPV	MOR=4,15+0,0022*Edyn	22		
Syl	MOEloc=$(-23,0676+0,0255*V)^2$	53	Scots p.	[15]
SylDuo	MOE=-10862+6,4216*V	73	Missanda	[16]
SylDuo	MOE=-13355+3,5020*V-1243*dh+13,95*ρ	71	Scots, Salzmann p.	[17]
	MOR=-50,03+0,0170*V-16,75*dc-21,35*dh-0,0045*L+0,08*ρ	65		
SylDuo	MOE=-1034+0,8733*Edyn [3]	68	Salzmann p.	[18]
SylDuo	MOE=330+0,7548*Edyn-416,55*Zrad+249,10*Zsco+0*Zsal	74	Radiata, Scots, Salzmann p.	[19]
	MOR=-3,65+0,0034*Edyn-10,52*Zrad-1,19*Zsco+0*Zsal	60		
SylDuo	MOE=789+0,7182*Edyn	67	Maritime p.	[20]
	MOR=2,64+0,0033*Edyn	29		
MST	MOE=370+0,7890*Edyn	69		
	MOR=0,40+0,0036*Edyn	30		
SylDuo	MOE_{EN384}=-14986+2,9826*V+17,95*ρ-6,54*dc+36,89*dh-267,79*Rw	68	Black poplar	[21]
SylDuo	MOE=1191+0,6197*Edyn	82	Radiata p.	[22]
	MOR=8,38+0,0028*Edyn	40		
MST	MOE=1358+0,6716*Edyn	78		
	MOR=8,33+0,0031*Edyn	40		
MST	Ln(MOE)=-16,4037+3,1708*Ln(V)+0,05359*Zp	94	Particle board and MDF	[23]
	Ln(MOR)=-0,9285+0,0020*V-0,6133*Zp	97		
MST	MOE_{EN384}=-2877+2,3000*V [4]	36	Black poplar	[24]
	MOE_{EN384}=-12296+2,6860*V+18,2*ρ	51		
SylTrio	MOE=384+0,7275*Edyn	56	Scots p.	[25]
	MOR=-7,65+0,0038*Edyn	31		
MST	MOE=1375+0,6357*Edyn	54		
	MOR=1,06+0,0031*Edyn	22		
SylDuo	MOE=$(-1847580+(2,44*V^2))^{1/2}$	90	Superpan boards	[26]
	MOR=64,42-(78347/V)	90		
MST	MOE=$(-1988380+(3,04*V^2))^{1/2}$	92		
	MOR=65,16-(72148/V)	93		
SylTrio	MOE=1529+0,7020*Edyn	71	Sweet chestnut	[27]
	MOR=8,90+0,0027*Edyn	14		
MST	MOE=3988+0,5670*Edyn	56		
	MOR=23,07+0,0018*Edyn	8		
IML MH	MOEplank=4,5*Vtree-579,42*BAL-86,5*G+374,6*H_0-125,9*DBH	55	Maritime p.	[28]
SylTrio	MOE_{EN384}=135+0,4479*Edyn	40	Paulownia	[29]
MST	MOE_{EN384}=-74+0,5951*Edyn	44		
SylDuo	MOE=-1471+0,8200*Edyn-438,89*Zrad+893,17*Zsco+329,53*Zsal+0*Zmar	90	Radiata, Salzmann, Scots, maritime p.	[30]
	MOR=-37,72+0,0080*Edyn-12,47*Zrad-3,75*Zsco-11,42*Zsal+0*Zmar	68		
USLab [5]	MOE=-1535+0,69*Edyn-451,50*Zrad+843,01*Zsco+339,68*Zsal+0*Zmar	90		
	MOR=-37,51+0,0067*Edyn-12,34*Zrad-4,00*Zsco-11,21*Zsal+0*Zmar	67		
MST	MOE=-1662+0,78*Edyn-428,70*Zrad+958,05*Zsco+232,23*Zsal+0*Zmar	90		
	MOR=-38,09+0,0075*Edyn-11,92*Zrad-2,71*Zsco-12,17*Zsal+0*Zmar	67		
BPV	MOE=-2521+0,93*Edyn	79	Scots p.	
	MOR=-37,06+0,0075*Edyn	53		
SylDuo	MOE=-743+0,9184*Edyn	85	Radiata, Salzmann, Scots, maritime p.	[31]
USLab [5]	MOE=-419+0,7483*Edyn	85		
MST	MOE=-1384+0,9131*Edyn	81		
PUNDIT	MOE=-1953+0,9417*Edyn [1,2]	73	Maritime p.	[32]
MST	MOE=-1518+1,2330*Edyn [1,2]	91		
SylDuo	MOE=-829+0,8391*Edyn	69	Salzmann p. [3]	[33]
USLab [5]	MOE=-1025+0,7350*Edyn	70		
MST	MOE=-95+0,7727*Edyn	67		
MST	MOEloc=608+0,8282*Edyn [4]	42	Salzmann, Scots p.	[34]
	MOR=5,02+0,0033*Edyn [4]	43		
USLab [5]	MOE=4807+0,3577*Edyn	53	Norway spruce [3]	[35]
USLab [6]	MOE=3279+0,4421*Edyn	62		
MST	MOE=2810+0,5916*Edyn	63		

Measurements in longitudinal direction: V ($m \cdot s^{-1}$) velocity. Edyn=$\rho \cdot V^2$ (MPa). ρ ($kg \cdot m^{-3}$) density. MOR (MPa). (MPa). MOEloc (MPa). MOE_{EN384}=MOE*1,3-2690 (MPa). Zrad, Zsco, Zsal and Zmar are constants for radiata, Scots, Salzmann and maritime pine, which are only equal to 1 for this species, for other species are 0; Zp is a constant for boards, which is equal to 1 for particleboards and 0 for MDF; L (mm) length; dc and dh=knottiness parameters; Rw=ring parameter; BAL, G, H_0 and DBH=forest inventory parameters. [1]Small clear specimens,[2]Three-point bending test, [3]Timber from existing structures,[4]Round timber, [5]45 kHz sensors, [6]22 kHz sensors, [7]Martínez 1992, [8]Rodríguez-Liñán and Rubio 1995, [9]Pedras *et al.* 1997, [10]Rubio 1997, [11]Hermoso 2001, [12]Hermoso *et al.* 2002, [13]Conde 2003, [14]Esteban 2003, [15]Hermoso *et al.* 2003, [16]Arriaga *et al.* 2006, [17]Conde *et al.* 2007, [18]Hermoso *et al.* 2007, [19]Íñiguez-González 2007, [20]Carballo *et al.* 2009b, [21]Casado *et al.* 2012, [22]Montón 2012, [23]Pérez-García 2012, [24]Casado *et al.* 2013, [25] Montero 2013, [26]Sevilla *et al.* 2013, [27]Vega 2013, [28]Merlo *et al.* 2014, [29]Cáceres-Hidalgo 2016, [30]Llana 2016, [31]Arriaga *et al.* 2017a, [32]Morales-Conde & Machado 2017, [33]Osuna-Sequera 2017, [34]Aira *et al.* 2019, [35]Arriaga *et al.* 2019.

Vibration techniques used to estimate properties

Longitudinal velocity from first mode natural frequency is calculated as the product of two times length and frequency. The dynamic modulus of elasticity (Edyn) was calculated as product of density and square velocity. Several authors have presented estimation models using vibration techniques (Table 2).

Several authors improved the prediction models of MOR by combining acoustic or vibration results with visual parameters. Hermoso (2001) found an absolute R^2 increase of 11 %, while the corresponding figure for Íñiguez-González (2007) was 15 % and for Arriaga *et al.* (2014) it stood at 4 %, including knottiness parameters.

Table 2: Mechanical properties estimation models by vibration techniques.

Device	MOE and MOR models (MPa)	R^2 (%)	Species	Reference
PLG	MOE=-338+1,1136*0,92*Edyn	77	Radiata p.	(3)
	MOR=0,81+0,0039*(0,92*Edyn-6,2*CKDR)	48		
MTG	MOE=44,50*$Edyn^{0,6305}$	50	Scots p.	(4)
	MOR=0,0829*$Edyn^{0,6719}$	46		
PLG	MOE_{EN384}=1153+1,04*(0,92*Edyn-6,2*CKDR)	65	Scots p.	(5)
	MOR=-40,53+0,08*f+0,07*ρ	44		
PLG	MOE=762+0,9599*Edyn-508,92*Zrad-354,98Zsco+0*Zsal	76	Radiata, Scots, Salzmann p.	(6)
	MOR=-3,85+0,0045*Edyn-10,67*Zrad-3,83*Zsco+0*Zsal	65		
PLG	MOE_{EN384}=-868+1,0022*(0,92*Edyn-6,2*CKDR)	82	Maritime p.	(7)
	MOR=-70,66+0,0746*f+0,0641*ρ	47		
PLG	MOE_{EN384}=92+0,7927*(0,92*Edyn)	54	Black poplar	(8)
	MOR=-13,08+0,0066*(0,92*Edyn)	41		
PLG	MOE=-13294+12,728*ρ+3,689*V	82	Douglas fir	(9)
	MOR=-43+0,0172*V	38		
PLG	MOE=-490+6,7702*f+11,10*ρ-262,72*C (1)	43	Spanish juniper	(10)
PLG	MOE=1642+0,8251*Edyn-1041,87*Zrad-176,01*Zsco+0*Zsal	72	Radiata, Scots, Salzmann p.	(11)
	MOR=1,30+0,0038*Edyn-13,25*Zrad-3,01*Zsco+0*Zsal	61		
PLG	MOE_{EN384}=-13704+2,9563*V+17,85*ρ+307,72*dc +62,86*dh-267,59*Rw	70	Black poplar	(12)
PLG	MOE=1538+0,7490*Edyn	85	Radiata p.	(13)
	MOR=7,95+0,0035*Edyn	47		
PLG	MOE=(-15+0,0040*V+0,0160*ρ-0,0010*L)*1000	74	Sweet chestnut	(14)
	MOR=50,08+0,0034*Edyn-22,0590*$kh^{1/2}$-0,0090*L	33		
PLG	MOE=353+0,8734*Edyn	63	Scots p.	(15)
	MOR=-9,37+0,0048*Edyn	37		
PLG (T)	MOE=3627+0,5564*Edyn	45		
	MOR=10,37+0,0028*Edyn	26		
PLG	MOE=1481+0,8230*Edyn	78	Sweet chestnut	(16)
	MOR=3,59+0,0036*Edyn	20		
HM200	MOE=2494+0,7270*Edyn	70		
	MOR=12,46+0,0028*Edyn	15		
PLG	MOE=1229+0,7566*Edyn	87	Radiata p.	(17)
	MOR=7,26+0,0035*Edyn	46		
PLG (T)	MOE=823+0,8112*Edyn	86		
	MOR=3,25+0,0040*Edyn	50		
PLG	MOE_{EN384}=357+0,5222*(0,92*Edyn)	42	Paulownia	(18)
PLG (TC)	MOE_{EN384}=-2436+0,9053*Edyn	41		
PLG	MOE=-226+0,90*Edyn-144,26*Zrad+ 1105,25*Zsco+814,85*Zsal+0*Zmar	92	Radiata, Salzmann, Scots, maritime p.	(19)
	MOR=-25,99+0,0087*Edyn-9,72*Zrad-1,80*Zsco-6,72*Zsal+0*Zmar	70		
MTG	MOE=-327+0,90*Edyn-139,37*Zrad 1119,60*Zsco+782,94*Zsal+0*Zmar	92		
	MOR=-26,92+0,0088*Edyn-9,66*Zrad-1,65*Zsco-7,03*Zsal+0*Zmar	70		
PLG	MOE=-740+0,9507*Edyn	80	Salzmann p. (2)	(20)
HM200	MOE_{EN384}=-5353+3,4*V	50	Radiata p.	(21)
	MOE_{EN384}=2160+2*V	43	Maritime p.	

Measurements in longitudinal or transversal (T) direction: V ($m \cdot s^{-1}$) velocity. Edyn=$\rho \cdot V^2$ (MPa). ρ ($kg \cdot m^{-3}$) density. f (Hz) frequency. MOR (MPa). MOE (MPa). MOEloc (MPa). MOE_{EN384}=MOE*1,3-2690 (MPa). Zrad, Zsco, Zsal and Zmar are constants for radiata, Scots, Salzmann and maritime pine, which are only equal to 1 for this species, for other species are 0; L (mm) length; CKDR, kh, dc and dh=knottiness parameters; C=taper parameter; Rw=ring parameter. (T)Transversal measurements, (TC)Transversal measurements on cantilever beam, (1)Round timber, (2)Timber from existing structures, (3)Arriaga *et al.* 2005[a], (4)Broto *et al.* 2007, (5)Casado *et al.* 2007, (6)Íñiguez-González 2007, (7)Casado *et al.* 2008, (8)Casado *et al.* 2009, (9)Santaclara *et al.* 2009, (10)Villanueva 2009, (11)Arriaga *et al.* 2012, (12)Casado *et al.* 2012, (13)Montón 2012, (14)Vega *et al.* 2012, (15)Montero 2013, (16)Vega 2013, (17)Arriaga *et al.* 2014, (18)Cáceres-Hidalgo 2016, (19)Llana 2016, (20)Osuna-Sequera 2017, (21)Vega *et al.* 2019b.

Probing techniques for density estimation

According to several authors (Bobadilla *et al.* 2007, Íñiguez-González 2007, Calderón 2012, Martínez 2016) no significant differences were found between radial and tangential measurements (with respect to annual rings). Furthermore, in the assessment of timber structures (the most common use for probing techniques) it is not usually possible to select the probing direction. Density estimation models using acoustic and probing techniques have been presented by several Spanish authors (Table 3).

Table 3: Density estimation models from Spanish research works.

Device	Variable	Density models (kg·m^{-3})	R^2 (%)	Species/product	Reference
BPV	ToF (µs)	ρ=752,4-0,3201*ToF	16	Maritime p.	(6)
BPV	Edyn (MPa)	ρ=634-0,0102*Edyn [1]	18	Scots p.	(7)
Pilodyn	Depth (mm)	ρ=711,9-13,9*D [1]	80	Scots p.	(8)
IML Resi F300	Amplitude (%)	ρ=385+21,02*A [1]	85	Scots p.	(9)
SWRM	Force (kN)	ρ=1000/(0,956276+(2,3611/F))	62	Scots p. [2]	(10)
Resistograph 3450-S	Area (%·cm^{-1})	ρ=153+1,51*Ar	56		
Pilodyn	Depth (mm)	ρ=744,6-22,2*D	35	Radiata, Scots, Salzmann p.	(11)
SWRM	Force (kN)	ρ=289,9+109,7*F	49		
Pilodyn	Depth (mm)	ρ=771,91-19,03*D-97,01*Zrad-63,19*Zsco+0*Zsal	59	Radiata, Scots, Salzmann p.	(12)
SWRM	Force (kN)	ρ=365,88+95,46*F-81,47*Zrad-38,53*Zsco+0*Zsal	64		
IML Resi F300	Amplitude	ρ=e^{6,13}+(0,23*logA)	68	Salzmann p.	(13)
SylDuo	Transversal Velocity (m·s^{-1})	ρ=497,60+0,0385*TV-75,53*Zrad-57,07*Zsco+24,50*Zsal +0*Zmar	34	Radiata, Scots Salzmann, maritime p.	(14)
MST		ρ=467,02+0,0697*TV-80,28*Zrad-56,09*Zsco+19,36*Zsal+0*Zmar	34		
Pilodyn	Depth (mm)	ρ=737,07-20,54*D-44,04*Zrad-11,00*Zsco+53,91*Zsal+0*Zmar	61		
SWRM	Force (kN)	ρ=389,29+89,61*F-92,99*Zrad -54,21*Zsco-8,30*Zsal+0*Zmar	67		
IML Resi E400	Amplitude	ρ =326+19*A	44	Radiata, Scots p.	(15)
Resistograph 3450-S	Area (%·cm^{-1})	ρ=394,797+0,7598*Ar	82	Salzmann, maritime, Scots p., sweet chestnut, European oak and walnut	(16)
SWRM	Force (kN)	ρ=174,749+64,4308*F	74	Black poplar	(17)
Pilodyn	Depth (mm)	ρ=700,193-15,9204*D	31	Radiata p.	(18)
SWRM	Force (kN)	ρ=285,40+103,77*F	53		
Core drill bit Ø16 [3]	Core ρ (kg·m^{-3})	ρ=53,6357+0,850184*CD	88		
MST	Velocity (m·s^{-1})	Ln(ρ)=5,42+0,000492*V+0,154*Zp	89	Particleboard and MDF	(19)
Pilodyn	Depth (mm)	ρ=13,849+5778/D	74	18 species	(20)
Pilodyn	Depth (mm)	ρ=622,932-11,6226*D	32	Scots p.	(21)
SWRM	Force (kN)	ρ=375,935+85,2801*F	33		
Pilodyn + SWRM	D (mm)+F (kN)	ρ=500,663-7,24375*D+54,694*F	41		
SylDuo	Velocity (m·s^{-1})	ρ=179,65+0,2193*V	97	Superpan boards	(22)
MST	Velocity (m·s^{-1})	ρ=178,39+0,2439*V	98		
SWRM	Force (kN)	ρ=341,74+227,458*F	90		
IML Resi-B 1280	Area/Length (bits)	ρ=204,4+20,487*Ar/L [1]	70	Pine [2]	(23)
Core drill bit Ø7 [3]	Core ρ (kg·m^{-3})	ρ=122,62+0,6668*CD [1]	48		
Pilodyn	Depth (mm)	ρ=709-15,52*D	30	Radiata p.	(24)
SWRM	Force (kN)	ρ=294+106,174*F	57		
Core drill bit Ø10 [3]	Core ρ (kg·m^{-3})	ρ=80+0,779*CD	80		
Core drill bit Ø16 [3]		ρ=87+0,827*CD	80		
Pilodyn	Depth (mm)	ρ=689,73-10,32*D-86,42*Zrad-28,69*Zsco+43,02*Zsal+0*Zmar	56	Radiata, Scots Salzmann, maritime p.	(25)
SWRM	Force (kN)	ρ=395,28+77,39*F-66,63*Zrad -13,21*Zsco+41,09*Zsal+0*Zmar	68		
Pilodyn	Depth (mm)	ρ=776,09-17,376*D [1]	51	Western red cedar, missanda, black poplar, sweet chestnut, oak, iroko, radiata, Scots, Salzmann, maritime p.	(26)
SWRM	Force (kN)	ρ=445,483+94,63*F [1]	53		
RML WoodEx	Chips Mass (g)	ρ=-97,59+428,66*ChM [1]	96		
IML Resi PD400	Amplitude (%)	ρ=226,770+8,569*A	66	Scots, Salzmann, Aleppo, A. pitch p.	(27)
IML Resi-B 1280	Resi ρ (kg·m^{-3})	ρ=421,9+0,3484*RD [1]	39	Maritime p.	(28)
Core drill bit Ø7 [3]	Core ρ (kg·m^{-3})	ρ=0,9594*CD [1]	67		
Pilodyn	Depth (mm)	ρ=(-128038+(4869150/D))$^{1/2}$ [1]	86	Same 10 species Martinez 2016	(29)
Wood Pecker [4]		ρ=e$^{[illegible]}$ [1]	75		
Core drill bit Ø10 [3]	Core Mass (g)	ρ=45+228*CM [1]	98	Same 10 species Martinez 2016	(30)
Pilodyn	Depth (mm)	ρ=538-7,25*D	22	Norway spruce [2]	(31)
Wood Pecker [5]		ρ=562-5,70*D	33		
SWRM	Force (kN)	ρ=349+64,69*F	53		
Core drill bit Ø10 [3]	Core ρ (kg·m^{-3})	ρ=209+0,47*CD	84		
Core drill bit Ø16 [3]		ρ=270+0,34*CD	89		
RML WoodEx	Chips Mass (g)	ρ=195+198,97*ChM	70		
Infrared Thermography	T 10 min (°C)	ρ=-2510,93+73,0357*T [1]	87	Sapele, moabi, beech, cherry, pine, oak, ipe	(32)
	T 30 min (°C)	ρ=-1705,75+73,3937*T [1]	97		
RML WoodEx	Chips Mass (g)	ρ=-30,79+383,13*ChM	84	Radiata, Scots Salzmann, maritime p.	(33)
	Chips ρ (kg·m^{-3})	ρ=90,39+0,871*ChD	81		
Pilodyn	Depth (mm)	ρ=837,41-25,99*D	42	Salzmann p. [2]	(34)
Wood Pecker [4]		ρ=974,74-27,76*D	57		
SWRM	Force (kN)	ρ=316,87+172*F	51		
RML WoodEx	Chips Mass (g)	ρ=35,94+343,06*ChM	76		

Zrad, Zsco, Zsal and Zmar are the constants for radiata, Scots, Salzmann and maritime pine, which are only equal to 1 for this species, for other species are 0; Zp is a constant for boards, which is equal to 1 for particleboards and 0 for MDF, (1)Small clear specimens,(2)Timber from existing structures,(3)Internal bit diameter (mm), (4)3 strikes, (5)5 strikes, (6)Martínez 1992, (7)Rubio 1997, (8)Palaia *et al.* 2000, (9)Mariño *et al.* 2002, (10)Casado *et al.* 2005, (11)Bobadilla *et al.* 2007, (12)Íñiguez-González 2007, (13)Vilches & Correal 2009, (14)Íñiguez-González *et al.* 2010, (15)Soto-Martínez 2010, (16)Acuña *et al.* 2011, (17)Casado *et al.* 2012, (18)Montón 2012, (19)Pérez-García 2012, (20)Cañas-Gutiérrez 2013, (21)Montero 2013, (22)Sevilla *et al.* 2013, (23)Morales-Conde *et al.* 2014, (24)Íñiguez-González *et al.* 2015ª, (25)Llana 2016, (26)Martínez 2016, (27)Camacho-Valero 2017, (28)Morales-Conde & Machado 2017, (29)Salamanca 2017, (30)Bobadilla *et al.* 2018, (31)Llana *et al.* 2018a, (32)López *et al.* 2018, (33)Martínez *et al.* 2018, (34)Osuna-Sequera *et al.* 2019b.

MC adjustment factors

Adjustment factors are important to achieve comparable results. Most research studies focus on MC influence. Palaia *et al.* (2000) showed that MC influence on ultrasound velocity measured on small clear specimens of Scots, maritime and Caribbean pitch pine varied with a power function. The higher the MC, the lower its influence. Rodríguez-Liñán and Rubio (1995), Llana *et al.* (2018b) and Llana *et al.* (2018c) reported two different tendencies in which slopes were steeper below fiber saturation point (FSP) than above it, where MC influence is considered insignificant. Table 4 therefore presents adjustment factors to a reference MC value of 12 %, below FSP, as proposed for Spanish-grown species by Equation 1, Equation 2 and Equation 3:

$$Vel_{12\%MC} = \frac{Vel_{MC}}{\left[1 - k_{MC} \times \left(MC - 12\right)\right]} \quad (1)$$

$$Depth_{12\%MC} = \frac{Depth_{MC}}{\left[1 + k_{MC} \times \left(MC - 12\right)\right]} \quad (2)$$

$$Force_{12\%MC} = \frac{Force_{MC}}{\left[1 - k_{MC} \times \left(MC - 12\right)\right]} \quad (3)$$

Where: $Vel_{12\,\%MC}$ ($m \cdot s^{-1}$) obtained from ToF or longitudinal frequency at 12 % of MC, Vel_{MC} ($m \cdot s^{-1}$) at a given MC, $Depth_{12\,\%MC}$ (mm) obtained by the Pilodyn 6J Forest NPR instrument, $Depth_{MC}$ (mm) at a given MC, $Force_{12\,\%MC}$ (kN) obtained by the SWRM instrument, $Force_{MC}$ (kN) at a given MC, k_{MC} (as per unit) adjustment factors, which are listed in Table 4.

Table 4: MC adjustment factors (k_{MC}) in % for Spanish-grown species (below FSP).

Device	Variable corrected	k_{MC} (%)	Species	Reference
BPV	Velocity	0,70 (1)	Scots p.	(2)
Pilodyn	Depth	1,16	Radiata p.	(3)
SWRM	Force	3,20		
PLG Hitman HM200	Velocity	1,20	Sweet chestnut	(4)
SylDuo	Velocity	0,70 (1)	Scots p.	(5)
BPV		0,59 (1)		
Grindosonic MK5	Edyn	1,06 (1)		
SylTrio	Velocity	0,48	Scots p.	(6)
MST		0,50		
PLG		0,65		
SylDuo USLab MST	Velocity	0,62	Radiata p.	(7)
		0,61	Scots p.	
		0,72	Salzmann p.	
		0,76	Maritime p.	
PLG MTG	Velocity	0,62	Radiata p.	
		0,63	Scots p.	
		0,73	Salzmann p.	
		0,76	Maritime p.	
Pilodyn	Depth	2,20	Radiata p.	(8)
		1,60	Scots p.	
		1,70	Salzmann p.	
		2,00	Maritime p.	
SWRM	Force	2,20	Radiata p.	
		2,80	Scots p.	
		2,50	Salzmann p.	
		2,10	Maritime p.	

(1) Small clear specimens, (2) Rodríguez-Liñán and Rubio 1995, (3) Calderón 2012, (4) Vega 2013, (5) Llana *et al.* 2014, (6) Montero *et al.* 2015, (7) Llana *et al.* 2018b, (8) Llana *et al.* 2018c.

Visual grading

In order to add a new species to the visual grading standard it has to be characterized. Several research works in Spain during the past 30 years focused on this characterization. Fernández-Golfín *et al.* (1998) summarized the works done in the INIA Structural Timber Laboratory during several years for the characterization of radiata, Scots and maritime pine that led to the production of the first version of the UNE 56544 (1997) standard with two visual grades (ME-1, ME-2). Fernández-Golfín *et al.* (2001) published the works involved in adding Salzmann pine in the same standard. The results from Íñiguez-González *et al.* (2007b) made it possible to introduce the new visual grade MEG in the UNE 56544 (2007) for large cross-section timber (thickness > 70 mm). Fernández-Golfín *et al.* (2007) characterized southern blue gum for the first version of the hardwoods visual standard UNE 56546 (2007). Correal *et al.* (2013) and Vega *et al.* (2013) proposed visual grading criteria for structural sweet chestnut that were included in UNE 56546 (2013). Preliminary characterization works were also performed for other species that were not included in standards, such as Spanish juniper (Díez *et al.* 2006). Furthermore, five Spanish species appear in the EN 1912 (2012), and another one has been approved (Table 5). The latest allocations in EN 1912 (2012) were approved according to the works of Vega *et al.* (2013) and Hermoso *et al*. (2016). A new revision of the Spanish visual grading standards would be recommendable following the works of Montón *et al.* (2015), Llana *et al.* (2019) and the new version of European standard EN 14081:1 (2016). Several research studies were published comparing visual grading according to the Spanish standard UNE 56544 and the German standard DIN 4074-1, (Díez *et al.* 2000, Conde 2003, Arriaga *et al.* 2005b, Adell *et al.* 2008, Llana *et al.* 2019). In general, more pieces are rejected using the Spanish standard based on knot evaluation. A research work into the load carrying capacity of timber pieces from existing structures (Arriaga *et al.* 2005b) proposed a visual grading procedure limited to the main parameters (knots and slope of grain) in an attempt to simplify and adapt the procedure used in new timber to in-situ grading particularities. Other works studied the practically zero influence of some defects, such as fissures and wanes, on mechanical properties (Arriaga *et al.* 2007, Esteban *et al.* 2010). Touza *et al.* (2013) proposed a new visual grading criterion for large cross-section American pitch pine specimens from existing structures, based on knots, grain slope and boring insect attacks. Arriaga *et al.* (2017b) showed that visual grading standards (designed for new sawn timber) lead to a high percentage of rejection in existing timber structures, and it is usually not possible to access all 4 faces. Furthermore, beam cross-section is not homogeneous (Osuna-Sequera *et al.* 2017). Vega *et al.* (2019a) found ineffective visual strength grading of 216 dry sweet chestnut small-diameter logs using EN 1927-1 (2008), EN 1927-2 (2008) and DIN 4074-2 (1958) standards.

Table 5: Correspondence between Spanish visual grades and strength classes according to the European standard EN 1912 (2012) and later approvals.

Species	(2)	Spanish visual grade				
		(3)			(4)	
		ME1	ME2	MEG	MEF	MEF-G
Salzmann pine	Strength class	C30	C18	C22		
Scots pine		C27	C18	C22		
Radiata pine		C24	C18	C20 (1)		
Maritime pine		C24	C18	-		
Southern blue gum					D40	-
Sweet chestnut					D27 (1)	D24 (1)

(1) Approved by CEN/TC124/WG2-TG1 in October 2014 and not yet included in (2)EN 1912 (2012), (3)UNE 56544 (2011),(4) UNE 56546 (2013).

ME1 and ME2: Madera Estructural de 1ª y 2ª (structural timber 1st and 2nd quality)

MEG: Madera Estructural Gruesa escuadría (large cross-section structural timber)

MEF: Madera Estructural de Frondosas (hardwood structural timber)

MEF-G: Madera Estructural de Frondosas de Gruesa escuadría (hardwood large cross-section structural timber).

Final discussion

To summarise, 68 mechanical property estimation models from 29 research works were collected in Table

1 (acoustic techniques), 43 estimation models from 19 research works were included in Table 2 (vibration techniques) and 60 density estimation models from 29 research works were compiled in Table 3 (acoustic and probing techniques). These estimation models were developed from 1992 to 2019 in Spain. Most of these estimation models are valid for the same species, e.g. 24 different models to estimate MOE of the Scots pine (Spanish reference wood species) from ultrasound, stress waves and vibration devices are presented. If these different models are used to calculate MOE from common Spanish-grown Scots pine measurement values (acoustic velocity 5400 $m \cdot s^{-1}$, vibration velocity 4750 $m \cdot s^{-1}$ and density 510 $kg \cdot m^{-3}$, values from Llana (2016)), the mean MOE value obtained is 11734 MPa with a coefficient of variation of 12,6 % and standard deviation of 1474 MPa. No significant differences between MOE results of acoustic and vibration techniques were found. From the point of view of the authors, the results should be further studied to elucidate whether the recommended mechanical property estimation models for different NDT devices and species should be included in a new standard or at least in a protocol. However, if end-users develop their own models, these can be used instead of the standardized models. Furthermore, several MC adjustment factors for Spanish-grown species are presented in Table 4 that would be also included in a new standard or protocol. NDT measurement procedures should be unified, e.g. Osuna-Sequera *et al.* (2019b) concluded that in order to increase the accuracy of density estimation using probing techniques, from three to five measurements in at least two different cross-section areas including the middle point are needed. This should be included in UNE 41809 (2014) as a measurement recommendation.

Better knowledge of the research undertaken should help to prevent overlapping between research groups' works and promote cooperation between them. Some research works presented here are almost unknown: e.g. several interesting and useful results were only published as final degree projects. In 2016 a net of Spanish-timber research groups was created under the name LIGNOMAD to find common objectives and promote collaboration. Research groups should identify potential research objectives, find other research groups with similar objectives and apply together for funding. Furthermore, useful information from previous research works compiled in this review paper can be helpful. E.g. a potential new topic is the reuse and recycling of recovered timber. In this review it was reported that at least one research group in Spain is working on this topic, and several estimation models for timber from existing structures were developed and visual grading criteria for timber from existing structures were proposed. Finally, apart from visual grading, NDT techniques are not used by the Spanish industry for grading purposes, while they are commonly used in most European countries. Therefore, closer collaboration between research groups and industry is needed to implement NDT for grading.

Future milestones

The main milestones that are expected to be achieved in the near future, given that some Spanish research groups are currently working on them, are: (1) a NDT grading standard for new structural sawn timber, (2) further implementation of NDT in Spanish timber industry, (3) assessment protocol for existing timber structures, including special guidelines for visual grading and for NDT use, (4) models for estimating properties in existing timber structures.

CONCLUSIONS

Most Spanish research works focus on NDT portable devices which can be used both in new sawn and round timber grading and to assess existing structures. These techniques are not used in practice in the Spanish industry for grading. However, they are frequently used to assess timber structures. Several statistical linear models for the estimation of mechanical properties using different NDT devices (68 models based on acoustic techniques, 43 based on vibration and 60 for density estimation) were developed in Spain from 1992 to 2019, most of them for new sawn timber.

The results obtained are very variable because the methods used are not exactly the same (size of the pieces, wood free of defects vs. structural size timber and the arrangement of measuring equipment, etc.). It is therefore difficult to extrapolate the use of a model for general application. It is very important that in the future different research groups use unified procedures (MC adjustment factors, number of measurements and the way to carry out them) to enhance the capacity of these techniques.

Although many research works have been published in Spanish and in Spanish conferences and workshops, fortunately in recent years more research has been published in English and in scientific journals, allowing international dissemination. Some useful research works presented here are almost unknown. Information from previous research works compiled in this review paper should help research groups to identify potential research objectives, find other research groups with similar objectives and avoid overlapping works.

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