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Structural products made of beech wood: quality assessment of the raw material

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ABSTRACT
Hardwood timber is becoming increasingly important in Europe for its use as structural material, both as solid wood and engineered structural products. In Italy, the great abundance of beech forests has recently led to a research project to investigate the use of this species in construction. A first step is the characterization of the raw material for the production of structural glued products. This requires developing the strength grading of beech boards, both by visual and machine methods. To the aim, four provenances were collected across the distribution of beech in Italy. The main strength reducing characteristics were measured visually, and the dynamic modulus of elasticity was determined before performing the destructive bending tests of sampled boards. Correlation between properties were similar to what is usually observed for softwoods with the exception of density, which did not correlate with any other property. Several visual rules and machine settings were developed and compared, showing the effectiveness of both methods for the strength grading of beech. The grading yields for the high strength classes were very similar for machine and visual grading, while the machine permitted to reduce the number of rejected elements when two grades were selected at the same time.

Keywords: strength grading, structural timber, Fagus sylvatica, visual grading, machine grading

1. Introduction

Increasing the use of hardwoods in structural applications is a relevant topic in Europe (Aicher et al. 2014). Several factors contribute to promoting the use of hardwoods in construction: Europe is rich in large, underused hardwoods forests; various European countries are encouraging re-afforestation with hardwood species to face forest disturbances such as windstorms; for this reason the use of hardwoods falls within the growing interest in timber as a sustainable material for bio-building. Overall, new perspectives for European hardwoods, namely ash, beech, sweet chestnut, and oak, can arise in the coming years in the construction sector.

In this context, beech wood is particularly interesting given the abundance of European beech forests that can regularly supply large-scale productions. The load-bearing attitude of beech wood has long been exploited by producing plywood for the transport sector or by using solid wood for heavy-load packaging. Conversely, the structural bonding of beech wood is known to be difficult. This is strictly related to its density and requires a fine-tuning of the bonding systems (Aicher and Ohnesorge 2011).

Nowadays, in Europe, glued laminate timber (GLT) and cross laminated timber (CLT) can only be made from coniferous or poplar wood according to the standards EN 10480 (EN 14080 2013) and EN 16351 (EN 16351 2015). Anyway, the growing interest in the structural use of hardwoods is confirmed by the recent constitution of a working group within the European Committee for Standardization (CEN-TC124/WG3/TG1). The group is currently working on the project "Timber structures - Glued laminated timber and glued solid timber made from hardwood species – Requirements". The aim is to draft a standard setting out provisions regarding the production glue laminated timber (GLT) made from hardwood and characterizing its mechanical properties. Over the years, the potential of beech wood in construction fostered several scientific studies that investigated the mechanical performance of sawn wood (Glos et al. 2004; Frese and Blass 2005; Glos and Denzler 2006; Aicher and Ohnesorge 2011; Cibecchini et al. 2016; Ehrhart et al. 2016a, b) and the gluing of boards (Aicher and Reinhardt 2007; Ohnesorge et al. 2010; Schmidt et al. 2010; Luedtke et al. 2015). A recent study (Ehrhart et al. 2018a) showed that beech GLT can reach strength classes up to GL 55 (characteristic bending strength of 55 MPa), with mean values of local bending Modulus of Elasticity (MoE) of 16,200 MPa. Considering that coniferous GLT is commonly used in Class GL 24, it can be seen how beech wood can broaden the applications of GLT and CLT in construction. Presumably, beech GLT and cross laminated timber (CLT) could compete with steel and concrete in heavy-load bearing uses. The increased mechanical performance could also be exploited for reducing the cross sections, allowing new architectural prospects and limiting the amounts of material used.

On the other hand, the high variability of the raw material requires an in-depth study of the characteristics that influence its mechanical performance and a careful analysis of the different strength grading methods in order to select the starting material at best (Ehrhart et al. 2016a; Westermayr et al. 2018). Currently the attention of glulam manufacturers is mainly addressed to materials of high structural quality, but this involves a high waste of the raw material (Torno et al. 2013). Only few studies investigated the low quality beech timber (Westermayr et al. 2018), which on the other hand can be present on the market and can be better used if selected effectively.

To make the use of structural wooden products safe, but at the same time efficient, these basic steps must be followed: (1) characterization of the raw material with the development of strength grading systems; (2) for the glued products, whether they are glulam beams or structural panels, the evaluation of the bonding quality.

The present study focuses on the characterization of the beech raw material that can be found in Italy and the development of visual and machine strength grading methods. The aim is laying the basis for the production of structural engineered products made from Italian beech wood, which can have positive effects on the national wood sector.

2. Materials and methods

2.1 Sampling

The collection of the raw material was defined in order to sample the distribution of beech in the Italian territory. Overall, 465 boards were sampled, divided into four origins as described in Table 1. The variability of the sample was obtained by collecting the timber from different geographical areas, covering the whole latitude of the country. Sub-samples were collected in the regions with high national percentages of beech forest area: 2 sub-samples (NE and NW) were collected in Northern Italy; 1 sub-sample in the centre (C) and 1 in the South (S).

The specimens were mostly boards, with squared cross sections and thicknesses ranging from 20 to 60 mm and widths from 100 to 150 mm, since the intended final used was the manufacturing of glued structural products.

Table 1 - Number of pieces sampled by cross-section size (thickness x width) and Italian geographical origin.

Cross section (mm)	Length (mm)	Provenance				TOT
		South (S)	North-East (NE)	North-West (NW)	Central (C)	
20x100	3100	53		29		82
25x100	4200		30			30
30x100	3200				44	44
20x120	3100	66				66
40x120	3700			39		39
45x120	4200		44			44
50x120	3800				34	34
50x150	3700			38		38
55x150	4200		45			45
60x150	3800				43	43
TOT		**119**	**119**	**106**	**121**	**465**

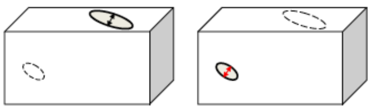
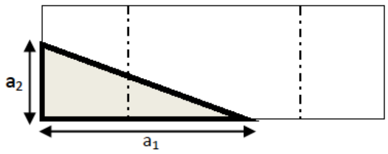
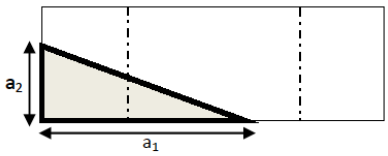
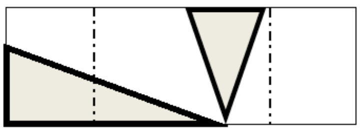
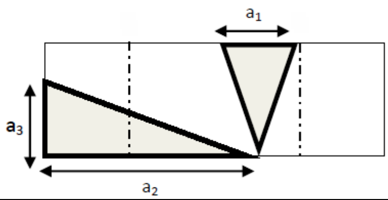
2.2 Visual and machine measurements and laboratory tests

As a first step, each board was examined by its visual characteristic: the main features visually detectable were measured and noted. Then the boards passed through a grading machine for the machine property measurement and afterward they were destructively tested to determine their physical and mechanical properties.

Concerning the visual inspection, it focused on what can be considered a strength-reducing characteristic: knots, slope of grain, ring width and presence of pith included in the cross section.

The knots were mapped in order to calculate several parameters: the position of each knot, as well as the minimum diameter and its projection on the side of the board were registered, and the calculations listed in Table 2 were made. For each board, the highest value of each knot parameter was selected for the further statistical analysis concerning knots.

Table 2 – Description of the knot parameters.

Symbol	Description	Scheme*	Equation[(1)]
		Single Knot	
KAR	Knot Area Ratio: ratio of the projected cross-sectional area of the knot ($\square$) to the cross sectional area of the piece.		$KAR = \square / (wt)$ (1)
Dm/S	Ratio of the minimum diameter of the knot ($\updownarrow$ or $\updownarrow$) to the dimension of the side.		$Dm/S = max\left\{\frac{\updownarrow}{t};\frac{\updownarrow}{w}\right\}$ (2)
Pr/S	Ratio of the knot projection (a_i) on the side to the dimension of the side itself.		$Pr/S = max\left\{\frac{a_2}{t};\frac{a_1}{w}\right\}$ (3)
sPr/2W	Ratio of the sum of the projections of the knot on the sides to the double width.		$sPr/2w = \frac{\sum a_i}{2w}$ (4)
		Grouped knots	
tKAR	Ratio of the sum of total projected cross-sectional areas of all knots ($\square$) in a length of 150 mm to the cross sectional area of the piece.		$tKAR = \square / (wt)$ (5)
tPr/2W	Ratio of the sum of the projections of all knots (a_i) in a length of 150 mm to the double width.		$tPr/2w = \frac{\sum a_i}{2w}$ (6)

(1) w = width of the cross section; t = thickness of the cross section

* schemes of knots by Microtec WebKnot Calulator http://knots.microtec.eu/

The slope of grain was measured as the general inclination of the wood fibres to the longitudinal axis of the timber piece. The measurement was made on a length of one metre following the fissures if present or by means of a swivel handle scribe, and expressed as a percentage (EN 1310 1997). The same measure was also executed after the destructive tests, taking advantage of the failure fissures to detect the grain direction. Local fibre deviations, for example close to knots, were ignored.
The presence of the pith included in the cross section was also registered and the average ring width was measured on the transversal section of the piece along the longest straight line normal to the growth rings (EN 1310 1997).

As for the machine measurement, the natural frequency of vibration in the longitudinal direction was measured by means of an industrial device (ViSCAN) for each specimen. The piece was placed on supports and percussion provided the excitation necessary to cause vibration; the natural frequency of vibration was measured by a non-contact laser interferometer.
The weight and dimensions of each piece were also measured and the dynamic modulus of elasticity was calculated by the following formula (Eq. 7):

$$E_{dyn} = IP_{MOE} = 4f^2L^2\rho \tag{7}$$

where f is the natural frequency of vibration, L the length of the timber piece and ρ is the density, calculated by the timber weight divided by its volume.

As a next step, four point edgewise bending tests were carried out in accordance with the European standard EN 408 (EN 408 2012), in order to measure the global and local static modulus of elasticity. The total span was 18 times the nominal depth and the shear span was 6 times the nominal depth. The local deformation was measured in the neutral axis on both sides of the timber piece and the mean of the two measures was used to calculate the local modulus (Eq. 8). In the same test setup, the total deformation was measured in the central point on the tension edge of the beam and used to calculate the global modulus of elasticity (Eq. 9). Then the load was applied until failure and the bending strength (f_m) was computed (Eq. 10).

$$E_{lo} = \frac{3al_1^2\Delta F}{4bh^3\Delta w_{local}} \tag{8}$$

$$E_{gl} = \frac{l^3\Delta F}{bh^3\Delta w_{global}}\left[\left(\frac{3a}{4l}\right) - \left(\frac{a}{l}\right)^3\right] \tag{9}$$

$$f_m = \frac{3aF_{max}}{bh^2} \tag{10}$$

With ΔF: the applied load increment, F_{max}: the load at failure, l: the length between the two supports, b: the thickness of timber piece, h: the width, a: the distance between the load point and the nearest support, l_1: the central gauge length, Δw_{local} and Δw_{global}: the deformation increments.

After testing, density and moisture content were determined in accordance with ISO 13061-1 (ISO 13061-2 2014) and EN 13183-1 (EN 13183-1 2002) (oven dry method) respectively, cutting a small specimen of full cross section from each timber piece. Density and modulus of elasticity values were corrected to a moisture content of u = 12% according to the adjustment equations suggested in EN 384 (EN 384 2016). Dynamic modulus of elasticity was adjusted to the reference moisture content using the same factor applied to the static modulus.
Measured values of bending strength were adjusted to a reference depth (*h*) of 150 mm using the $k_h = (150/h)^{0.2}$ factor calculated in accordance with EN 384 (2016).

2.3 Data analysis

Descriptive statistics were calculated for all the properties measured visually, by the machine and during the laboratory tests. Correlations between all the properties were determined by means of Pearson correlation coefficient and linear regression analysis.
Finally, machine and visual grading were performed according the European standardization and the yields were compared.

2.3.1 Derivation of machine settings
According to the machine grading system described in the EN 14081-2 (EN 14081-2 2018), before it can grade, a machine must be "calibrated" to the specific timber species and provenance. This means that the proper settings have to be derived through appropriate statistical procedures. The methods used in the present work were those specified in the EN 14081-2 (2018) and summarized below.
The basic approach is to set thresholds for the property measured by the machine (called Indicating Property, IP) so to group the sampled pieces into strength classes. Subsequently, a series of verifications are applied to validate such thresholds. Firstly, the required characteristic values of the grade determining properties (GDP, read bending strength, modulus of elasticity and density determined in laboratory by destructive tests) for the strength class assigned to the timber pieces shall be met both for the entire sample and for each provenance (sub-sample). Then, a cost analysis performed as already described in a previous paper (Nocetti et al. 2016). Briefly, the cost analysis compares the assignment to a class made by the machine based on the IP with the optimum grading, that is the assignment based on timber mechanical properties determined by laboratory tests. Specific weighting factors are applied for wrongly graded pieces; particularly adverse factors are given for incorrectly upgraded pieces.
The IP used here was the dynamic modulus of elasticity; the k_v factor provided by the EN 384 (2016) for machine grading was not applied (Stapel and Van de Kuilen 2013; Nocetti et al. 2016).
The required characteristic values of the strength classes are reported in the EN 338 (EN 338 2016), while the methods to calculate the characteristic values are described in the EN 14358 (EN 14358 2016) and EN 384 (2016). For the calculations, the local modulus of elasticity was used, since it does not need any adjustment for shear stresses as global does (Nocetti et al. 2013).

When all the verifications were met, the thresholds constituted the settings used by the machine for grading.

2.3.2 Visual grading rule and strength class assignments

The visual grading approach is based on the set up of specific limitation to the visual characteristics, in order to group the timber pieces into quality groups (grades) (EN 14081-1 2016). Afterwards, the characteristics values of the GDPs are calculated for each grade to assign it to a strength class as defined in the EN 338 (2016).

Here, the limitation to the visual properties was set in order to get two grades and the rejects (pieces not suitable to structural use). For the assignment to the strength classes, the provision of the EN 384 (2016) was applied: for each grade, the characteristics values of the GDPs were calculated according to the EN 14358 (2016) separately by provenance (sub-sample) and only for the sub-samples with at least 40 pieces. Then they were weighted averaged and the adjustment (k_n) for the number of the sub-samples was applied. According to the k_n factor, the less is the number of the sub-samples and the highest is the reduction of the characteristic values.

The assignment of a grade to a strength class was achieved when the characteristic values of that grade calculated as above met the requirement of the class.

3. Results and discussions

3.1 Quality of the raw material

The average values and the variability of the mechanical and physical properties as a result of the destructive tests are reported in Table 3. The dynamic modulus of elasticity measured by the grading machine is also shown for each sub-sample and for the whole dataset. The visual characteristics are summarized in Table 4. Considering the two tables together provides a complete description of the raw material. As a first observation the sub-sample NE had by far the worst quality: the boards had the lowest mechanical properties (both strength and stiffness) and the knots were more and bigger. Also the variability of the mechanical properties is higher than in the other sub-samples. Very high variability was earlier observed in low quality material tested in Germany (Westermayr et al. 2018).

On the other hand, the three other provenances had a very similar average bending strength, comparable to what was previously observed for Italian beech (Cibecchini et al. 2016), but differentiated by stiffness and knottiness. The sub-sample S had the highest modulus of elasticity (both static and dynamic), but higher values of the knot parameters if compared to NE and mainly NW, the last with the smallest values of knot parameters among the four provenances. This does not mean that the knots of S boards were larger, but that their size, compared to the size of the boards, was higher. It should be remembered, in fact, that all the pieces in the sub-sample S had the minimum tested thickness of 20 mm.

Besides, looking at the number of knots (Kn in Table 3) and the percentage of pieces with the pith included in the cross section, sub-sample S and NW showed the lowest average values. This indicates that the boards were probably cut from the outer part of the logs (due for instance to larger stems) or that in the sawing

pattern the pith was often discarded. On the contrary, in the sub-samples NE and C more than the 20% of the pieces had the pith included, denoting that also the inner part of the logs was kept during sawing.
As for density, S had the heaviest timber (and the widest rings), while the other provenances did not differ from each other. Anyhow, the variability of density was extremely low, with a coefficient of variation less than 6%. The same was already noticed and reported for beech (Glos et al. 2004).
As a whole, the analyzed sample has a high variability, useful for verifying the effectiveness of different grading methods.

Table 3 – Average values of the mechanical and physical properties measured during destructive bending tests and of the machine measurement. Coefficient of variation between brackets.

Property	Symbol	Unit	Provenance				all
			S	NE	NW	C	
Bending strength	$f_{m,mean}$	(MPa)	74.3 (29.7)	58.5 (39.1)	74.2 (31.3)	74.6 (31.3)	69.4 (34.6)
Global MoE	$E_{g,0,mean}$	(GPa)	14.6 (13.9)	10.8 (17.3)	13.4 (15.8)	12.6 (14.2)	12.8 (18.7)
Local MoE	$E_{l,0,mean}$	(GPa)	15.2 (17.6)	10.9 (21.9)	13.9 (19.3)	13.3 (17.0)	13.3 (22.2)
Dynamic MoE	$E_{dyn,mean}$	(GPa)	15.2 (11.3)	12.6 (15.3)	13.8 (12.1)	14.0 (12.7)	13.9 (14.5)
Density	ρ_{mean}	(kg/m^3)	752 (6.0)	701 (4.7)	714 (4.5)	700 (4.4)	716 (5.8)

Table 4 – Average values of the visual properties. Symbols of the knots explained in Table 2.

Property	Symbol	Unit	Provenance				all
			S	NE	NW	C	
Knottiness (n. of knots)	Kn	(-)	1.39	2.07	1.05	1.56	1.54
Single knot	KAR	(-)	0.17	0.19	0.08	0.11	0.14
	Dm/S	(-)	0.32	0.45	0.22	0.22	0.30
	Pr/S	(-)	0.36	0.48	0.25	0.26	0.34
	sPr/2W	(-)	0.20	0.23	0.12	0.14	0.17
Knot cluster	tKAR	(-)	0.18	0.21	0.09	0.12	0.15
	tPr/2W	(-)	0.21	0.26	0.13	0.16	0.19
Slope of grain (visual)	SGv	(%)	2.6	1.7	2.1	2.3	2.2
Slope of grain (after test)	SGa	(%)	5.4	2.8	4.5	2.8	4.0
Ring width	W	(mm)	3.5	2.8	3.0	2.2	2.87
Pith (boards with pith)	P	(%)	6.7	24.4	8.5	23.1	15.9

3.2 Correlations between properties

The relationships between the several properties were investigated by linear regression analysis and the results are presented in Table 5.
In general, for the whole sample, correlations between strength and stiffness's (both static and dynamic modulus of elasticity, fig. 1) have shown trends and values similar to those found in similar works for softwoods and higher to what was observed in the past for other hardwoods (Nocetti et al. 2010, 2016; Vega

et al. 2012). For beech, Ehrhart et al. (2016a) found a lower correlation between tensile strength and dynamic modulus of elasticity ($R^2 = 0.22$), while Westermayr et al. (2018) for the same properties reported a correlation similar to our findings ($R^2 = 0.5$).

Density was not correlated neither with bending strength nor with the modulus of elasticity, as reported in several previous works on beech (Cibecchini et al. 2016; Ehrhart et al. 2016a; Westermayr et al. 2018); neither the ring width showed any significant correlation with density. This is not unusual for hardwoods, so that the sorting of structural quality material is difficult to base on density (Nocetti et al. 2010, 2016).

The relationships of the knot parameters with the mechanical properties were again as good as what observed for softwood, and much better than the results previously achieved for hardwoods (Nocetti et al. 2010). Among the several knot parameters calculated, the higher values of the coefficient of determination were detected for sPr/2W and tPr/2W (Fig. 2), even if also the values for the other parameters were not very far. Earlier studies reported a correlation value r = -0.67 between KAR and tensile strength (Glos et al. 2004) or coefficient of determination $R^2 = 0.53$ again between KAR and tensile strength and $R^2 = 0.52$ between DEB (the same parameter here called sPr/2W) and strength (Ehrhart et al. 2016a). On the contrary, Westermayr et al. (2918) for low quality beech reported lower correlations between knots and tensile strength ($R^2 = 0.15$ for KAR and $R^2 = 0.18$ for DEB)

Concerning the remaining visual features measured, the slope of grain was not related to any of the mechanical properties, neither the grain deviation measured before testing, nor the one determined after failure. The correlation was calculated both for the whole sample and only for the pieces with failure due to the slope of grain, but no significant results were observed. The explanation could be found in the well-known difficulties in detecting and therefore measuring the real grain deviation only by visual means (Cibecchini et al. 2016; Westermayr et al. 2018), but also keeping in mind that here the general direction of the grain is considered, and not the local deviation due to the presence of knots or other defects, as provided by the standard EN 14081-1 (2016). Local grain deviation, indeed, could be an efficient predictor of the mechanical properties of beech wood, but should be better determined using specific instruments (Ehrhart et al. 2018b).

Finally, the presence of the pith included in the timber piece was a significant factor affecting both bending strength and the modulus of elasticity, but not density (Westermayr et al. 2018). Pieces with the pith included had a mean strength of 61.1 MPa and a local modulus of elasticity of 12.2 GPa against the values of 70.9 MPa and 13.5 GPa for the same properties for the boards with the pith not included. Other properties (density and visual properties) were compared between pieces with and without pith. The only significant difference was observed for the knottiness, with the pieces including the pith having a higher number of knots (3 on average) against the pieces without pith (1.3). However, on average, the knot parameters, which consider the dimension of the knots related to the timber size, did not differ between pieces with and without pith, meaning that the knot size is a characteristic not useful to evaluate the reduction of strength due to the presence of the pith.

Table 5 – Coefficient of determination (R^2) of the relationship between bending strength (f_m) and local modulus of elasticity (E_l) and the other mechanical, physical and visual properties. Symbols are explained in Tables 2 and 3.

		$E_{l,0}$	$E_{g,0}$	E_{dyn}	ρ	KAR	Dm/S	Pr/S	sPr/2W	tKAR	tPr/2W
f_m	S	0.33	0.34	0.30	0.05	0.33	0.24	0.26	0.40	0.30	0.36
	NE	0.63	0.64	0.48	0.08	0.42	0.39	0.38	0.49	0.44	0.51
	NW	0.59	0.59	0.45	0.04	0.56	0.55	0.50	0.56	0.55	0.52
	C	0.73	0.68	0.55	0.00	0.55	0.46	0.55	0.59	0.58	0.63
	all	0.57	0.54	0.47	0.00	0.44	0.43	0.44	0.51	0.45	0.51
E_l	S	-	0.78	0.53	0.07	0.16	0.14	0.17	0.20	0.15	0.19
	NE	-	0.83	0.64	0.02	0.44	0.31	0.31	0.47	0.45	0.49
	NW	-	0.92	0.72	0.02	0.37	0.40	0.32	0.35	0.39	0.36
	C	-	0.91	0.76	0.01	0.47	0.41	0.49	0.53	0.50	0.56
	all	-	0.89	0.71	0.05	0.27	0.29	0.29	0.31	0.28	0.34

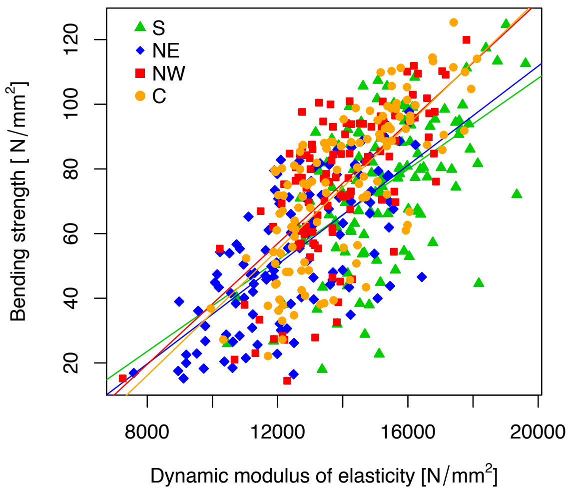


Figure 1 – Relationship between bending strength and dynamic modulus of elasticity (R^2 = 0.47).

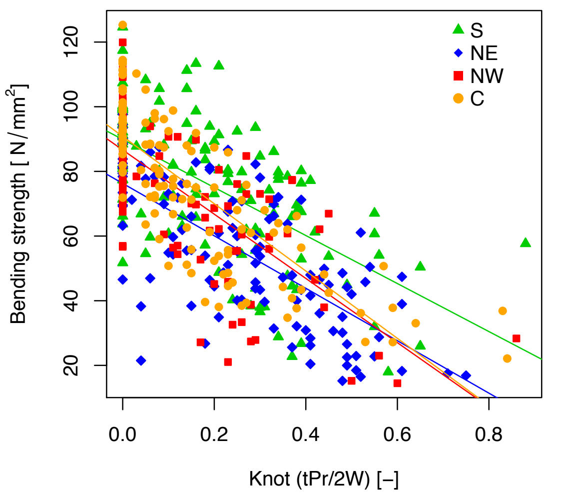


Figure 2 – Relationship between bending strength and knot parameter (R^2 = 0.51).

3.3 Strength grading

In view of the results above described, the parameters used for the development of visual grading rules were the knots and the presence of pith, as the only characteristics that affected significantly the mechanical quality of the material. Regarding the knots, only limitations for the single knot were established while the knot clusters have been disregarded. This decision was supported by the relatively poor presence of grouped knots: the ratio of KAR to tKAR was on average 0.96 and the ratio of sPr/2W to tPr/2W was 0.98, an indication of the infrequent presence of more than one knot within a distance of 150 mm.

Four grading rules were developed (Table 6): in the visual grading rules 1 (V1), the Dm/S parameter was used; in the visual grading rules 2 (V2), sPr/2W was the knot parameter taken into account. The choice was due on one hand to the determination of the minimum knot diameter, which is a very common measure in many grading rules already established (included the Italian one), and on the other hand to the selection of the sPr/2W parameter as the one with the highest correlation with mechanical properties.

The grading rules were developed to maximize the timber quality (D45-D24-R) or, alternatively, to minimize the rejects (D45-D18-R). Two grades were always selected by each grading rule (S1 the better grade and S2 the lowest); the limitation for the knot parameters for each grade are reported in Table 6. The presence of the pith was permitted only in the pieces to be assigned to grade S2, while the presence of any kind of damage was never permitted.

Table 6 – Description of the visual grading rules: limitation for the parameter used, characteristics values achieved and assignment to strength classes for the visual grades. NP = Not Permitted; P = Permitted

	Visual grading rules							
	V1_D45-D24-R		V1_D45-D18-R		V2_D45-D24-R		V2_D45-D18-R	
Grade	S1	S2	S1	S2	S1	S2	S1	S2
Knot parameter	Dm/S	Dm/S	Dm/S	Dm/S	sPr/2W	sPr/2W	sPr/2W	sPr/2W
Knot limitation	≤0.2	≤0.7	≤0.2	≤0.8	≤0.2	≤0.4	≤0.2	≤0.7
Pith	NP	P	NP	P	NP	P	NP	P
Damage	NP	NP	NP	NP	NP	NP	NP	NP
f_{mk} (MPa)	47.9	25.3	47.9	20.7	47.9	24.6	47.9	18.3
$E_{0,mean}$ (GPa)	15.1	11.8	15.1	11.3	14.9	11.5	14.9	10.9
ρ_{mean} (kg/m^3)	610	623	610	624	615	613	615	615
Assignment	D45	D24	D45	D18	D45	D24	D45	D18

In order to compare the visual and the machine grading, the machine settings were developed for the same combinations of strength classes achieved with the visual grading. The obtained settings (thresholds of dynamic modulus of elasticity) were: 14200 / 10400 MPa for the combination D45-D24-R and 14200 / 9120 MPa for D24-D18-R

Both the machine and the visual grading were applied to the beech boards and a strength class was assigned to each piece. The yields achieved with the different grading methods are shown in figure 3.

As first observation, beech is confirmed to be a species with high mechanical performance, since almost 50% of the pieces analysed could be assigned to the class D45 and another 45% to the class D24.

Comparing the machine to the visual grading, the machine allowed to minimize the number of rejects (4.3% for the combination D45-D24-R and 1.1% for D45-D18-R), as already determined for softwood (Brunetti et al. 2016); but the percentage of pieces graded as D45 were comparable.
Next, comparing the grading rules V1 and V2, the two knot parameters allowed for the same assignments of the visual grades, but the rules using sPr/2w had better yields, both in terms of the number of pieces in the higher class and in terms of fewer rejects (almost equalling the machine grading).
However, the Dm/S parameter seemed more versatile despite having slightly lower correlations with the mechanical properties: raising the limitation for the grade S1 from 0.2 to 0.25 the assignment could be D40, while raising the same limitation to 0.33 the assignment to D35 was possible. This could not be achieved with sPr/2W.
Focusing on the single provenances, the sub-sample NE displayed the lowest yields, reflecting the quality of the raw material and confirming the effectiveness of the strength grading on beech. For the other provenances the yields were comparable, even if differences were noticed between machine and visual grading mainly in the sub-sample S, for which the machine selected a higher number of D45 in respect to the visual grading, and in the sub-sample NW, for which the opposite was noticed, with the visual grading selecting a far higher number of D45. The explanation could be found in the characteristics of the raw material: the two sub-samples had the same mean bending strength (the limiting property for the assignment to the strength classes), but S showed higher stiffness (i.e. high yields with machine grading) and worse values of the knot parameter (i.e. low yields with visual grading). The contrary could be observed for NW, with lower values of modulus of elasticity and low values of knot parameter.

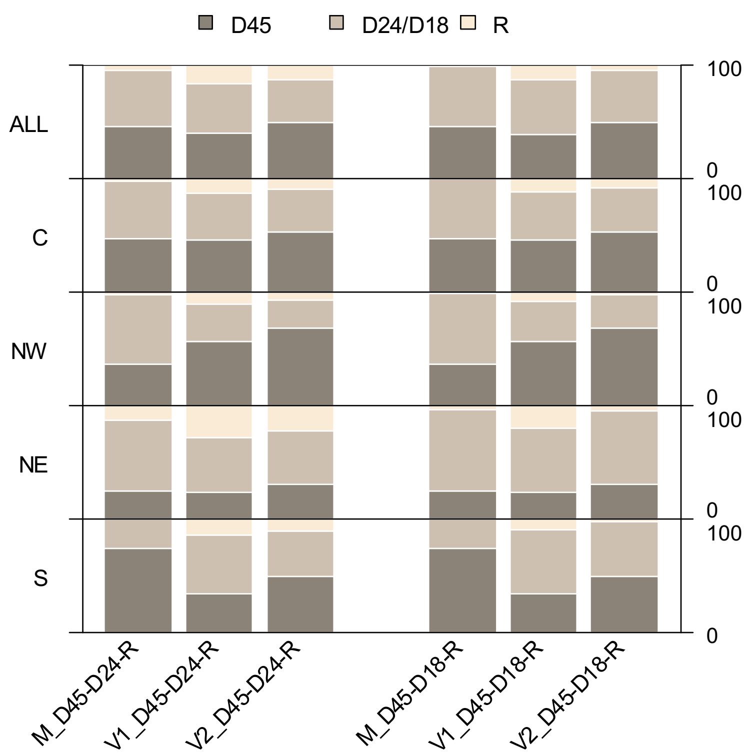


Figure 3 – Yields (%) achieved by means of the machine grading (M) and the visual grading rules described in Table 6. The yields are reported for each provenance and for the whole sample.

Finally, here are few remarks on the development of the grading methods. During the development of the settings for the machine, the sub-sample NE penalized the achievement of very high strength classes because of the verification prescribing that the characteristics values of the strength class shall be met for each provenance. This verification was introduced in the new version of the standard EN 14081-2 (2018).
In the same way, the assignments of the visual grades to strength classes were penalized by the number of sub-sample: at least 5 sub-samples are required to avoid reductions in the characteristics values because of the application of the k_n. Therefore, with a bigger sample, higher assignment for the grades or more permissive limitation for the visual characteristics could be achieved.

4. Conclusions

The quality of the raw material can be very variable with beech. At time, most of the attention is paid to the high quality pieces to produce very high performing structural products, therefore, a suitable grading system could reduce waste and increase yields with a view of a more sustainable and efficient use of the wood resource.
The strength grading was very effective for beech timber: machine grading, as well as visual grading, worked properly both with good quality boards and with weaker pieces and the yields reflected the quality of the raw material. Currently, no grading machine is certified at European level to grade beech timber, while few visual grading rules exists: in Germany the national standard (DIN 4074-5 2008) allows the assignment of the higher grade (LS13) to D40 and the second one (LS10 & better) to D35 (Glos and Denzler 2006; EN 1912 2012). Our results were in line with the German grading, with the possibility to assign the best grade to the higher class D45.
The grading yields for the best class (D45) were very similar for machine and visual grading, while the machine permitted to reduce the rejects, if two grades are selected at the same time. Moreover, correlations between machine and visual properties with the mechanical properties of beech timber were similar to what often observed for softwood, with the exception of density that does not correlate neither with strength or stiffness nor with ring width. Hence, the suggestion to exclude density from the grading of hardwood seems reliable.
In the future, the strength grading of beech could be further improved with a more effective determination of local grain deviation, which could be a significant factor in predicting the strength and stiffness of hardwood material. Machine grading, but also combined machine-visual grading could be implemented with the use of instrumentation suitable to the purpose.

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Conflict of interest

There is no conflict of interest.

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