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ORIGINAL

Timber tensile strength in mixed stands of European beech (*Fagus sylvatica* L.)

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Abstract

The conversion to climate-stable, resilient and productive forests has resulted in an increasing share of mixed stands. Different growth conditions and silvicultural treatments lead to an increased scatter in strength compared to what is expected from monoculture experience. The study (i) quantified the magnitude of variation in strength of European beech timber from stands of different composition and (ii) showed the impact of grading on the characteristic strength value of timber coming from those stands. Strength grading models and machine settings for hardwood tensile classes on over 900 European beech (*Fagus sylvatica* L.) boards were derived. One model used only the dynamic modulus of elasticity (E_{dyn}), and a more complex model used a knot value in addition. Afterwards, 407 boards from pure beech stands as well as mixed stands of beech with Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Norway spruce (*Picea abies* (L.) Karst.), sessile oak (*Quercus petraea* (Matt.) Liebl.), and Scots pine (*Pinus sylvestris* L.) were graded and analyzed for their material properties from tension tests parallel to grain. Although a variance components analysis attributed only 4.2% of the variation to mixture, the ungraded timber showed significant strength differences between the pure and the beech-pine stands (65.2 versus 46.6 MPa). The yield of the material graded to the highest class in a class combination was higher in pure beech stands. The required characteristic strength values were mostly met for boards from the pure stands; while boards from the beech-pine mixed stands hardly ever reached the required values. To reduce strength variation and guarantee reliable timber products, strength grading should consider the various growth situations in forests when sampling material for the derivation of settings.

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Introduction

Wood varies naturally in its properties. In recent years and across the entire forest chain, research projects have analyzed the influence of silvicultural treatment, forestry management strategies and site conditions on the physical and mechanical properties of timber. The studies focused mainly on some of the economically most important tree species: Sitka spruce (Brazier and Mobbs 1993; Moore et al. 2009b, a; Simic et al. 2018), radiata pine (Downes et al. 2002; Lasserre et al. 2009), Douglas fir (Barrett and Kellogg 1984; Krajnc et al. 2019), *Pinus patula* (Erasmus and Wessels 2020; Erasmus et al. 2020), Norway spruce (Høibø et al. 2014; Fischer et al. 2015, 2016), Scots pine (Høibø and Vestøl 2010; Auty et al. 2014), Japanese larch (Fujimoto and Koga 2009) or birch (Cameron et al. 1995) among others. To make the most use of the forest resource available regarding yields and mechanical properties, information on wood characteristic variation and sources of variation is essential (Moore et al. 2013), in particular how the wood properties vary on the different scales (stands, trees, boards). Variations in mechanical properties such as strength and stiffness have an impact on the definition of growth areas (Ridley-Ellis et al. 2016), on the modeling of wood properties (Giroud et al. 2017) and on the grading process (Ridley-Ellis et al. 2016). Understanding variations in wood characteristics, their causes, and the relevance of the observed scale (stand, tree, board) for the variation of the timber properties, provides essential insights for future forest management plans. As the entire grading process relies strongly on the standard, such knowledge on variation might support the standardization in timber industry, increase the reliability of the achieved mechanical properties and guarantee strength and stiffness. Datasets containing information on forest, tree, log, and board characteristics are required to quantify the variation in mechanical wood properties along the production chain (Moore et al. 2013; Fischer et al. 2016; Rais et al. 2022). Some studies could break down the total variation in mechanical properties into different levels via variance component analysis (VCA), i.e., using random-effects models and the overall mean of the dependent variable as fixed effect to estimate the amount of the variance components' contribution to the total variability in the dependent variable (Schützenmeister and Piepho 2012). Moore et al. (2013) for Sitka spruce and Fischer et al. (2016) and Vestøl et al. (2016) for Norway spruce were able to assign approximately 80% of the total variation in strength values to within-stand differences; less than 20% was attributed to between-stand differences. In other investigations, mixed models with fixed and random effects were used. Fixed effects not only reduced the overall variance of the dependent variable that was explained, but they also shifted the proportion of variation explained by random effects. As a result, the findings on the variance components' contribution of those investigations can only be interpreted as guidelines. For example, Rais et al. (2014) found that only 9% of the total variation in bending strength was attributed to between-stand variation—mainly due to initial spacing—, with the remaining 90% attributed to within-stand differences whereas in Moore et al. (2009a) thinning contributed to 10% of the total variation in bending strength.

For structural safety and for an economic use of structural timber, the strength either from bending or tension tests, stiffness and density of a population need to be assessed (Ridley-Ellis et al. 2016; Brunetti et al. 2021; Plos et al. 2022). These three properties are the so-called grade determining properties (GDPs) and are the ones used to assign timber population to a specific strength class (Ridley-Ellis et al. 2022). The strength classes of EN 338 comprise the timber design properties. For the GDP, those are fifth percentile of strength and density and mean modulus of elasticity. For softwoods, EN 338 introduces C-grades (based on bending testing) and T-grades (based on tension testing). Hardwoods such as poplar are handled as softwoods and classified in the C- and T-grades due to the similar physical and mechanical property profiles (EN 338). The same is true for chestnut which shows relatively low density compared to temperate hardwood species, such as ash, beech, and oak (Brunetti et al. 2013; Nocetti et al. 2016). For hardwoods, the EN 338 only lists bending strength classes, so called D-grades. Tensile strength classes for hardwoods were recently proposed by Kovryga et al. (2016, 2020). During the assignment, the characteristic values of the three GDPs are observed. The basis for the timber strength grading provides the measurement of the indicating properties (IPs). These properties comprise non-destructively measured wood properties and/or their combinations and are used to predict the GDPs. The boards' IPs are mostly calculated by a (multiple) linear equation. Estimating its regression coefficients needs large dataset containing destructive data (strength) and non-destructive machine data. By means of the parametrized model, a single board's strength can be predicted based on its machine data.

Machine strength grading is based on powerful predictors of wood quality; the non-destructive assessment of every piece of timber takes place at a faster rate with less risk of human errors than in visual grading (Ridley-Ellis et al. 2016). As already mentioned, the models for calculating the IPs and therefore the IPs themselves can be either based on a single parameter such as the knottiness, or on a combination of parameters and are the basis for the strength grading. EN 14081 assumes that IPs have a defined relationship to the GDPs within both a species and a grading region. The use of robust IPs in strength grading minimizes the unexplained variance of strength. In addition to the model's complexity, the class combination has an impact on the strength variance reduction inside a class (Rais et al. 2022). The IPs used, may describe up to 75% of the strength variation of some timber samples (Ranta-Maunus et al. 2011). The European machine-controlled system according to EN 14081 relies on so-called growth areas for which different models and settings are intended to minimize the uncertainty in the strength prediction. The present notion of growth areas is based on political national borders, without considering explicitly for existing inter-country differences in strength related to site characteristics (climate, soil), silviculture, or sawing pattern. The sample used to derive models and settings should be representative for the material to be graded in production in terms of origin, dimension and the wood quality (EN 14081–2).

The present investigation is dedicated to the silvicultural influence of the tree species mixture on the strength grading. Bending or tensile strength are often the limiting timber property in European strength grading, which is related to knot size and is in turn strongly influenced by silviculture (Gil-Moreno et al. 2019).

European beech (*Fagus sylvatica* L.) is the most common hardwood tree species in central Europe (Brus et al. 2012) and is the dominant tree species in most stands. It plays an important role in sustainable mixed stands (Pretzsch and Schütze 2021). For structural applications, there are promising products such as glued laminated timber (Pöhler et al. 2006). The current literature on the mechanical properties of beech timber comprises a variety of publications showing a broad range of possible mechanical property values. Westermayr et al. (2018) used a low-quality beech timber with characteristic properties matching the requirements of T-classes regarding the tensile strength (< 30 MPa). In contrast, Ehrhart et al. (2016) used high-quality beech lamellas to obtain characteristic tensile strength of 50 MPa. European beech is a very adaptive tree species in terms of stem and crown structure (Pretzsch 2019), but very little information is currently available on the source of the variation in the mechanical properties of European beech wood.

Previous research on European beech has found stiffness differences amongst 1907 boards originating from different species mixtures (Rais et al. 2020b). From the original sample, 407 boards representing pure and mixed stands were chosen for the current investigation. Destructive tests were used to see how the species mixing affects the timber strength. Not only strength differences were studied, but also whether grading can handle timber from varied forest managements and assure grade characteristic values.

(1) quantify the magnitude of variation in strength properties of European beech timber from stands with different tree species composition (pure stand versus mixed stand) and
(2) show the impact of machine strength grading on the characteristic strength value of timber coming from these different stands.

Material and methods

European beech boards from different mixture types

A sample of 407 boards was used for this study (Table 1). The sawn timber originated from 100 European beech (*Fagus sylvatica* L.) trees from 20 stands. All stands were located in two enterprises of the Bavarian State Forests (Bayerische Staatsforsten) in the Spessart, a low-mountain range located in Lower Franconia in the north of Bavaria, which is known for its extensive beech and oak forests. The stands were on average 125 years (y) old (standard deviation 32 y) and of good wood quality, as low-quality trees were removed in previous thinning interventions. Each tree and therefore each board could be assigned to one of the following mixture types: pure beech stands and mixed stands that included the tree species Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco), Norway spruce (*Picea abies* L. Karst.), Scots pine (*Pinus sylvestris* L.) and sessile oak (*Quercus petraea* (Matt.) L.), respectively. Apart from the mixing type, sources of variation were attempted to be minimized by sampling in the same region with similar soil conditions, climatic conditions, genetic material, altitude, and forest managements (*ceteris-paribus*-conditions): The

Table 1 Mean value and coefficient of variation (CoV) of timber characteristics of 407 European beech specimens separated into the five different species mixtures: *Fagus sylvatica* in pure stands and mixed with *Pseudotsuga menziesii*, *Picea abies*, *Quercus petraea* and *Pinus sylvestris*, respectively. The variables ρ_{dyn}, EF_{dyn} and E_{dyn} are wood density, eigenfrequency and dynamic modulus of elasticity, respectively. The variables $DAB_{testing}$ and $DAB_{grading}$ are knot values defined in DIN 4074–5, the subscripts refer to the section DAB was calculated: "grading" respected the full board length, "testing" a shorter section of the board only including the free test length

		Fagus sylvatica (n = 84)		*Pseudotsuga menziesii* (n = 84)		*Picea abies* (n = 76)		*Quercus petraea* (n = 82)		*Pinus sylvestris* (n = 81)	
		Mean	CoV[%]	Mean	CoV[%]	Mean	CoV[%]	Mean	CoV[%]	Mean	CoV[%]
Width	mm	129.2	1	129.3	0	129.3	1	129.2	1	129.4	1
Thickness	mm	38.0	0	37.9	1	37.9	1	38.0	0	38.0	1
Length	mm	2414	0	2414	0	2414	0	2413	0	2414	0
ρ_{dyn}	kg m^{-3}	702	5	685	5	690	5	681	4	689	4
EF_{dyn}	s^{-1}	984	8	973	8	976	6	965	6	948	6
E_{dyn}	MPa	15,900	16	15,100	16	15,300	13	14,800	13	14,400	12
$DAB_{testing}$	-	0.13	117	0.18	81	0.14	89	0.19	75	0.19	69
$DAB_{grading}$	-	0.14	109	0.21	78	0.17	81	0.21	69	0.22	63
Moisture content	%	9.9	14	10.1	13	9.9	14	9.4	11	10.1	14

sample contained only one cross-section, which is, however, relevant for production. The sampling area was located in one and the same area of about 300 km^2 to keep the site conditions and silvicultural history as uniform as possible. With a coefficient of variation of 56% for the strength of the ungraded boards (Table 2), the data nevertheless revealed high variation, which was comparable to other data on European beech (Rais et al. 2021).

The sample in the current study was representatively drawn from an original dataset containing 1907 specimens, which contained two cross sections $50\times150\times4100$ mm^3 and $40\times80\times4100$ mm^3 as described by Rais et al. (2020b) . Because 50×150 mm^2 is more typical for glued laminated timber where tensile strength is required in applications and influences the design, the current study's dataset only included boards from the bigger cross section. However, the subsample of 407 boards was chosen from the original sample (n = 1907) so that it was representative in terms of dynamic modulus of elasticity (E_{dyn}) and contained at least one board per log and per tree.

E_{dyn}-based machines are commonly used in strength grading because they are easy to operate and have a high throughput speed. More important, E_{dyn} demonstrates a strong link to strength and stiffness. E_{dyn} is calculated from wood density ρ_{dyn}, eigenfrequency EF_{dyn}, length, and moisture content u. The board length was originally 4.1 m. For the tension testing according to EN408, the position where failure was expected to occur was determined visually and regarded as the critical section. Afterwards, board length was reduced to 2.4 m. As the boards were planed, the dimensions of the 407 boards were reduced from $50\times150\times4100$ mm^3 to $38\times130\times2400$ mm^3. Prior to testing, a non-destructive assessment of the boards was done measuring E_{dyn} and the knot cluster value DAB defined in DIN 4074–5. The DAB takes into account all knots that appear in a moving window of 150 mm. The spread of all knots over the 150 mm window is related to the board's width. The knots' size (width) is measured parallel to the edge (Kovryga et al. 2019). Knot dimensions that overlap are considered only once. The DAB is a useful grading criterion for the mechanical properties of boards/planks and estimated the knot volume related to the board volume over 150 mm. E_{dyn} values were corrected to a moisture content of 12% according to EN 384 ($\Delta E_{dyn}\ \Delta u^{-1} = -1\%\ \%^{-1}$). Density ρ_{dyn} was

Table 2 Summary statistics (number N, mean value and coefficient of variation CoV) for the sample used for the derivation of models and settings. Sample D was the only sample used for strength grading

Literature	Sample	N	Tensile strength $f_{t,0}$		Static modulus of elasticity $E_{t,0}$		Density ρ	
			Mean	CoV	Mean	CoV	Mean	CoV
			MPa	%	GPa	%	kg m^{-3}	%
Glos and Lederer (2000)	A	217	48.7	46	13.8	18	723	6
Westermayr et al. (2018, 2022)	B	203	41.8	69	11.3	26	742	7
Westermayr et al. (2018)	C	100	49.7	65	11.7	27	748	7
Current study, see Table 1	D	407	53.8	56	15.0	19	719	5

calculated from the mass and the volume of the full board. The board mass in turn was determined using a scale. For volume determination, a measuring tape provided board length and a digital caliper provided board width and thickness.

The destructive tensile test was done in accordance with EN 408 and EN 384. For the tensile strength the free test length was set to nine times the nominal width of 130 mm with the critical section located within the tested range. The tensile strength values were adjusted to the reference width of 150 mm using the k_h-factor as required by EN 384. The specimens were gripped by jaws on both endings. Static modulus of elasticity $E_{t,0}$ was determined over five times the width. If possible, the $E_{t,0}$ was determined in the linear range of the stress–strain diagram between 10% and 40% of the maximum stress. Following testing, density and moisture content were determined cutting a small specimen from each test piece in accordance with EN 408 and EN 13183–1 (oven dry method), respectively. Similar to E_{dyn}, $E_{t,0}$ values were corrected to a moisture content of 12% according to EN 384 ($\Delta E_{t,0}\ \Delta u^{-1} = -1\%\ \%^{-1}$). Density values were adjusted to a moisture content of 12% according to EN 384 ($\Delta\rho\ \Delta u^{-1} = +0.5\%\ \%^{-1}$). For a variance component analysis (VCA), a random-effects model was applied to divide the random variance into variances being attributable to the different levels (mixture type, stand, tree and board). A nested structure was assumed for the random effects in accordance with the experimental design:

$$f_{t,0,ijkl} = \mu + M_i + S_{j(i)} + T_{k(ji)} + \varepsilon_{l(kji)}$$

where $f_{t,0,ijkl}$ was the measurement of the tensile strength of an individual board and μ was the overall mean. VCA was also conducted with $E_{t,0,ijkl}$, $E_{dyn,ijkl}$, and ρ_{ijkl}. Parameters M_i, $S_{j(i)}$ and $T_{k(ji)}$ were nested random effects at (species) mixture, stand-in-mixture, tree-in-stand-in-mixture levels (Pinheiro and Bates 2000; Zuur et al. 2009). The random effects were assumed to be normally distributed with zero mean and constant variance. The symbol $\varepsilon_{l(kji)}$ represented the independent and identically distributed random errors at board level.

Derivation of grading models and threshold values

There were neither models nor threshold values of strength classes (settings) for grading hardwood in tensile classes available at this time. As a result, we calculated both using European beech data from the wood database of the Professorship of Wood Technology (TU Munich). This dataset included 927 boards from four different projects (Table 2), whereas one project included the 407 boards already described and named sample D. The three other samples A, B, and C differed regarding their origin and cross section. Sample A originated from the forestry office Kirchheim (Baden-Wuerttemberg). The timber was cut from stems that could not be used for furniture production (Glos and Lederer 2000). An overall number of 104 and 115 boards with cross sections of 32 × 120 × 3080 mm^3 and 32 × 160 × 3450 mm^3 were available. Sample B consisted of beech lamellas from central Germany collected within a radius of 150 km around Creuzburg (Thuringia) as described in Westermayr et al. (2018, 2022). The dataset included

203 specimens with cross sections of 24×100 mm^2 and 24×150 mm^2 with 104 and 99 lamellas each and a length of approximately 3050 mm. Sample C is part of the ongoing project “Easy beech”, which is a continuation of the research by Westermayr et al. (2018). The cross section was 24×100 mm^2. Both a simple and a more complex strength grading model were derived. The simple model $Model_{simple}$ used E_{dyn} only, i.e., $f_{t,0} = f(E_{dyn})$, and achieved a coefficient of determination r^2 of 0.44; the complex model $Model_{complex}$ combined E_{dyn} and DAB, i.e., $f_{t,0} = f(E_{dyn}, DAB)$, and achieved a r^2 of 0.64.

$$Model_{simple} : IP_{simple} = -65.1 + 8.13 \times 10^{-3} \times E_{dyn}$$

$$Model_{complex} : IP_{complex} = -8.45 + 5.24 \times 10^{-3} \times E_{dyn} - 87.9 \times DAB$$

The setting for a strength class was the minimum threshold value that just fulfilled the requirements for tensile strength, tensile modulus of elasticity and density. Requirements for strength classes were not reduced by any of the factors given in the standard and the cost matrix was not applied. Individual strength classes or strength class combinations were optimized to maximize the yield of highest classes. Characteristic values were calculated according to the parametric approach of EN 14358. The tensile strength profiles (Table 3) for hardwood proposed by Kovryga et al. (2020) were applied. Those profiles comprise the relationships between the mechanical properties optimized for the tension test results of medium-density European hardwoods, such as ash and beech. Particularly, for the mentioned profiles, the proposed DT-classes exceed the limits of softwood T-classes regarding the characteristic tensile strength, which in cases of T-classes is set to maximum 30 MPa for T30. Although Kovryga et al. (2020) proposed to apply the use of T-classes for lower classes even for hardwoods, for consistency of the nomenclature used, only DT-classes were used here. In total, 16 strength class combinations were considered with either one or two strength classes for the boards to be assigned to. The following four strength class combinations including DT18 were analyzed: DT38/DT18/reject, DT42/DT18/reject, DT50/DT18/reject and DT18/reject. In analogy to DT18, strength class combinations were built with DT22, DT25 and DT28 as the lowest class, respectively. The free statistical software R was used for all statistical analysis (R Core Team 2019).

Table 3 Tensile strength classes (DT-classes) for medium-density hardwoods proposed by Kovryga et al. (2020) with the required characteristic values for tensile strength ($f_{t,0,k}$), tensile modulus of elasticity ($E_{t,0,mean}$) and density (ρ_k)

DT-classes	$f_{t,0,k}$ [MPa]	$E_{t,0,mean}$ [GPa]	ρ_k [kg m^{-3}]
DT50	50	17.0	640
DT42	42	16.0	620
DT38	38	15.5	620
DT28	28	13.5	550
DT25	25	12.5	550
DT22	22	11.5	550
DT18	18	10.0	550

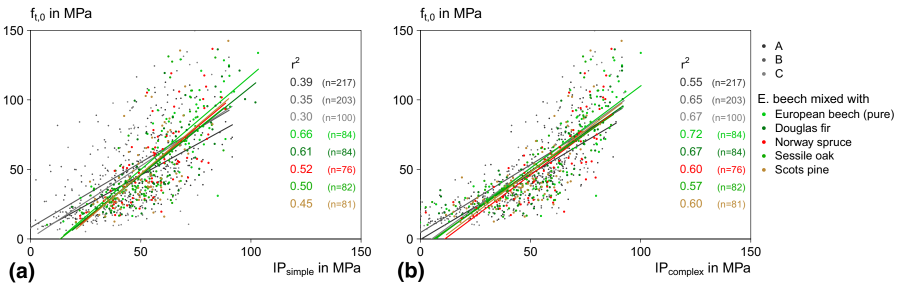

Fig. 1 Model$_{simple}$ explained 0.44 of the tensile strength variation, the r^2 varied between the species mixtures from 0.30 until 0.66, Model$_{complex}$ 0.64 ranging from 0.55 until 0.72. (Color online)

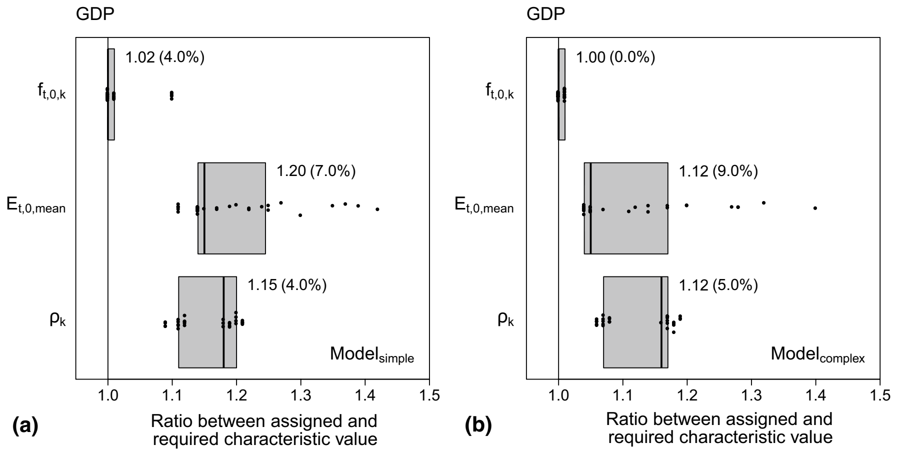

Fig. 2 Ratio between the achieved characteristic property value and the requirements for grading into 28 classes of different combinations is shown in boxplots with superimposed 1D jittered scatterplots. The tensile strength $f_{t,0,k}$ was the most critical GDP for the simple (**a**) and the complex (**b**) model. Figures in brackets show the coefficients of variation

Results

Derivation of models and threshold values

In Fig. 1, the strength $f_{t,0}$ is plotted against the IPs. Regression lines and the coefficients of determination r^2 for each sample A, B, and C are shown, whereas Sample D is subdivided into its five different sub-samples from different species mixtures. Independent of the strength class or class combination, the most critical GDP was characteristic strength value $f_{t,0,k}$. The ρ_k overfulfilled the required characteristic values by 15% for Model$_{simple}$ and 12% for Model$_{complex}$, the $E_{t,0,mean}$ by 20% and 12%, respectively (Fig. 2). Figure 2 is based on 28 classes from the 16 strength class combinations studied.

Table 4 ercentage of total variation in $f_{t,0}$, $E_{t,0}$, E_{dyn}, and ρ attributable to each stratum: mixture type M_i, stand $S_{j(i)}$, tree $T_{k(ji)}$ and board $\varepsilon_{l(kji)}$

	Stratum			
	M_i	$S_{j(i)}$	$T_{k(ji)}$	$\varepsilon_{l(kji)}$
$f_{t,0,ijkl}$	4.2%	1.1%	9.5%	85.2%
$E_{t,0,ijkl}$	4.1%	9.1%	19.7%	67.1%
$E_{dyn,ijkl}$	2.6%	12.5%	22.1%	62.8%
ρ_{ijkl}	3.7%	10.6%	49.4%	36.3%

Table 5 Mean value and standard deviation in brackets of timber characteristics ($f_{t,0}$, $f_{t,0,k}$, $E_{t,0}$, E_{dyn}, ρ) of the five species mixtures. Different lowercase letters above the figures indicate a significant difference at $p < 0.05$ (ANOVA), the applied ANOVA took into account the hierarchical data structure

		Fagus sylvatica (n = 84)	*Pseudotsuga menziesii* (n = 84)	*Picea abies* (n = 76)	*Quercus petraea* (n = 82)	*Pinus sylvestris* (n = 81)
$f_{t,0}$	MPa	65.2 (32.6)^{a}	52.7 (30.2)^{b,c}	55.4 (28.5)^{a,c}	49.0 (27.8)^{b,c}	46.6 (26.9)^{b,c}
$f_{t,0,k}$	MPa	19.8	16.7	18.1	16.3	15.7
$E_{t,0}$	GPa	16.2 (3.2)$^{a,1)}$	14.9 (3.1)^{a}	15.4 (2.6)^{a}	14.4 (2.7)^{a}	14.3 (2.2)^{a}
E_{dyn}	GPa	15.5 (2.4)$^{a,2)}$	14.8 (2.3)^{a}	15.0 (1.9)^{a}	14.4 (1.9)^{a}	14.1 (1.6)^{a}
ρ	kg m^{-3}	735 (39)$^{a,3)}$	715 (37)^{a}	720 (41)^{a}	708 (35)^{a}	718 (35)^{a}

[1] The F-statistics revealed a F-value of 2.2 and a *p*-value of 0.08, no post-hoc tests were done

[2] The F-statistics revealed a F-value of 1.8 and a *p*-value of 0.14, no post-hoc tests were done

[3] The F-statistics revealed a F-value of 1.7 and a *p*-value of 0.16, no post-hoc tests were done

Mechanical properties related to stand mixture

The majority of the total strength variation was not explained by differences between mixture types, stands, or trees and was therefore attributed to the board level (85.2%) based on the sample of 407 boards; 4.2% of the total variation were observed between different mixture types (Table 4). Of the variation in $f_{t,0,ijkl}$, 1.1% was attributed to differences at the stand-in-mixture level and with 9.5% of the total variation in $f_{t,0,ijkl}$ attributed to differences at tree-in-stand-in-mixture level. The high proportion of 49.4% of the total variation in timber density attributed to the tree level is obvious. The tensile strength distributions $f_{t,0}$ from pure and mixed stands differed significantly from one another (F-value of 2.7; *p*-value of 0.035). In particular, the European beech boards from pure stands had significantly higher strength values than from mixed stands with Douglas fir, oak or pine (post-hoc tests, Table 5). The differences in stiffness and density between mixture types were not significant.

The sample from pure stands achieved the highest characteristic strength values for the ungraded sawn timber, the sample from mixed beech-pine stands the lowest (Table 5).

A strength class DT50 could be set out for both models, i.e., the model based solely on the E_{dyn} and the model based on knottiness and E_{dyn}. The yield for DT50 using $Model_{simple}$ was 12.5% (51 of 407 boards); the majority with 20 boards came

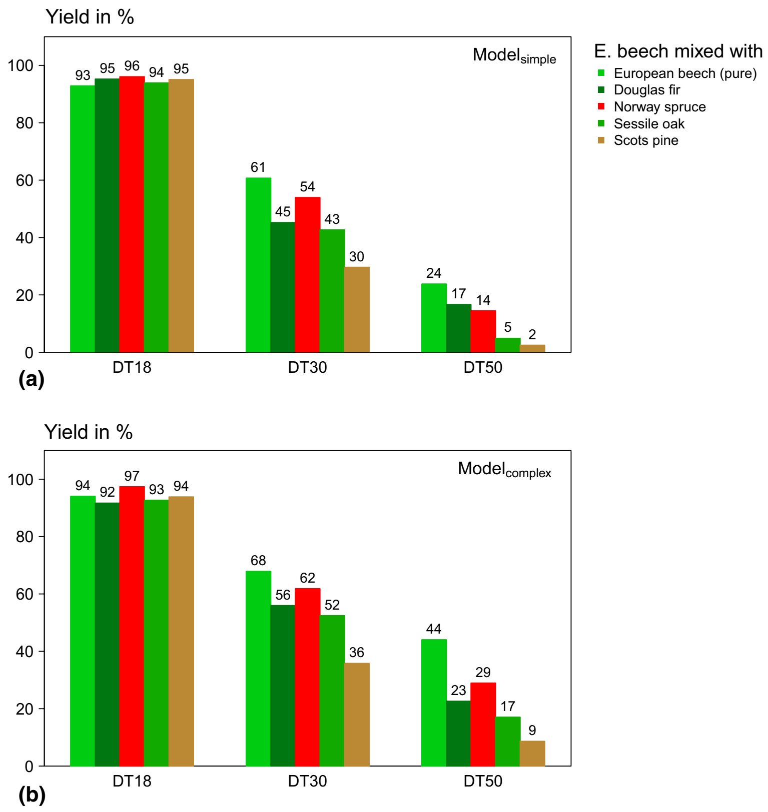

Fig. 3 Yields of a selection of single strength classes depending on the model. All 407 boards from different mixture types were graded once with Model$_{simple}$ (E_{dyn}) and once with Model$_{complex}$ (E_{dyn} and DAB). (Color online)

from the pure beech stands, the minority with two boards from the mixed beech-pine stands. As a result, based on the simple model, 24% of the boards from pure stands could be classified to DT50, whereas just 2% of the boards from beech-pine stands were (Fig. 3a). In comparison, the yield for DT50 using Model$_{complex}$ was 24.3% (99 of 407 boards). A share of 44% of the boards from the pure stands was assigned to DT50 (Fig. 3b). Among all mixture types and independent of the model, the yields were similar for the low grade DT18 when grading only one class in one run. All yields were higher than 90% (Fig. 3).

Figure 4 shows the deviation from the strength requirement for the high-strength classes DT38, DT42 and DT50. Figure 4 focuses on the higher strength class of the considered class combinations, Fig. 5 and Fig. 6 on the second lower class. Apart from the boards from the beech-spruce mixture in DT50 (Model$_{complex}$), the random samples of all mixture types, classes and models met the strength requirements. The samples from the beech-oak and beech-pine stands had less than 20 boards in the high class, so that the characteristic strength value was not calculated.

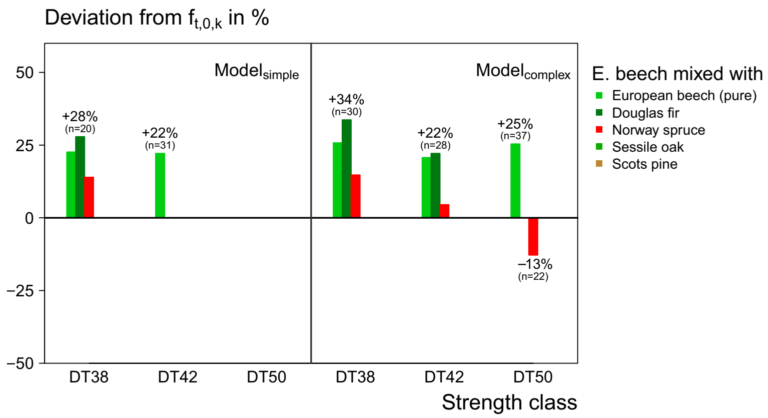

Fig. 4 Deviations of the characteristic strength value from the required characteristic strength values for DT38, DT42 and DT50 using Model$_{simple}$ (left) and Model$_{complex}$ (right). The bold figures next to the bars are the most positive and negative deviation among the mixture types for each combination, numbers in brackets are the number of boards. Bars are only illustrated if more than 20 boards were available. (Color online)

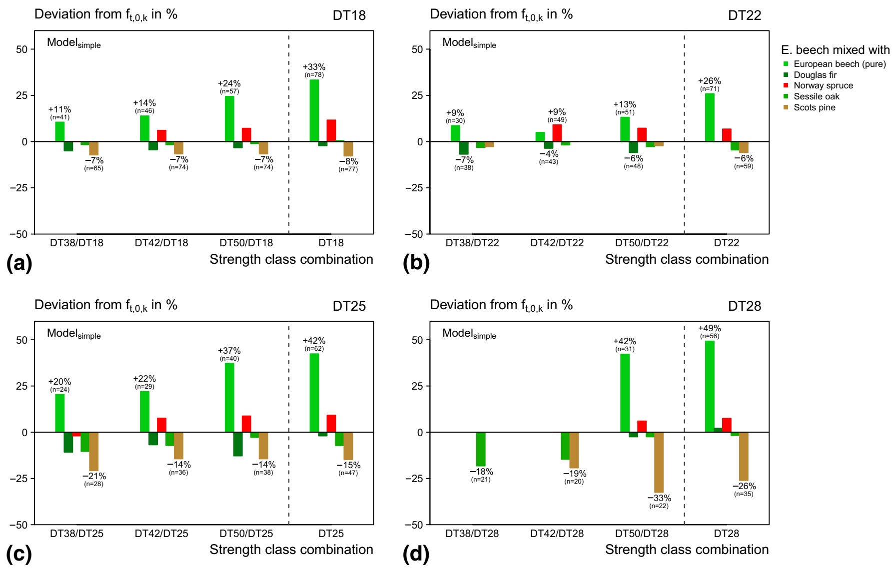

Fig. 5 Deviations of the characteristic strength value from the required characteristic strength values for DT-classes DT18 (**a**), DT22 (**b**), DT25 (**c**) and DT28 (**d**) using Model$_{simple}$. The bold figures next to the bars are the most positive and negative deviation among the mixture types for each combination, numbers in brackets are the number of boards. Bars are only illustrated if more than 20 boards were available. (Color online)

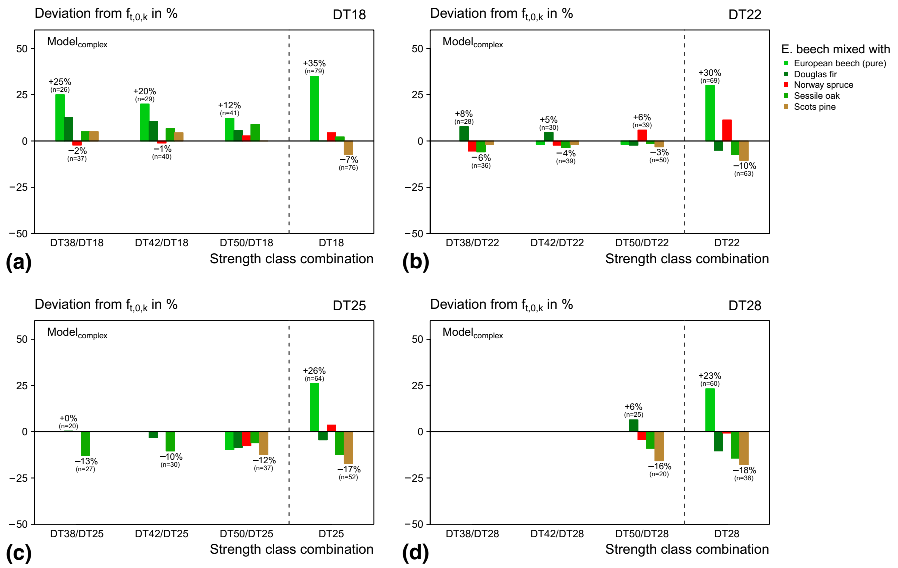

Fig. 6 Deviations of the characteristic strength value from the required characteristic strength values for DT-classes DT18 (**a**), DT22 (**b**), DT25 (**c**) and DT28 (**d**) using $Model_{complex}$. The bold figures next to the bars are the most positive and negative deviation among the mixture types for each combination, numbers in brackets are the number of boards. Bars are only illustrated if more than 20 boards were available. (Color online)

European beech timber from pure beech stands achieved the tensile strength requirement of classes DT18, DT22, DT25 and DT28 in almost each combination. Positive deviations in Fig. 5 and 6 indicate that the requirement has been exceeded, negative deviations indicate that it has not been met. In three combinations, the required characteristic tensile strength for the class with lower requirements in grade class combination was not fulfilled: by −2% for DT42/DT22 (Fig. 6b), by −2 for DT50/DT22 (Fig. 6b) and by −10% for DT50/DT25 (Fig. 6c). Because the higher-quality material was grouped in the top class, grading boards to two classes in one run reduced positive deviations in the class with lower requirements, if compared to the grading to the same lower class as a single class. The highest positive deviation was seen with $Model_{simple}$ for strength class DT28 in combination with DT50 (Fig. 5d), where the characteristic strength of boards from pure stands was 49% higher than required. On the other end of the spectrum, the characteristic strength of boards from beech-pine stands for DT28 in combination with DT50 (Fig. 5d) had the largest negative deviation, with the fifth percentile being 33% lower than necessary.

Seven times using $Model_{simple}$ and four times using $Model_{complex}$, the characteristic value of beech-pine stands missed the required strength value by more than 10%. Boards from beech-oak stands showed mainly negative deviations but only five combinations were lower than −10%: DT42/DT28 and DT38/DT28 based on $Model_{simple}$ and DT38/DT25, DT28 and DT25 based on $Model_{complex}$. Boards from beech-spruce stands did not deviate a lot. They never missed the requirement for a strength class by more than 10%; the lowest deviation was at DT50/DT25 when the benchmark for DT25 was missed by 8% ($Model_{complex}$). Boards from beech-Douglas fir stands only missed once the requirement for a class by more than 10% at DT38/DT25 with −11% ($Model_{simple}$).

Discussion

The VCA assigned the predominant part of the strength scatter to the board level; a smaller part was attributable to variations between trees, stands and mixture types (Table 4). Although only 4.2% of the total variation in strength could be attributed to between-mixture variation, an ANOVA revealed significant strength ($f_{t,0}$) differences between mixture types. The ANOVA on stiffness ($E_{t,0}$) did not show significant differences amongst mixture types. The *p*-value was with 0.079 slightly above the significance level of 0.05 (Table 5). In a related study, Rais et al. (2020b) applied a mixed model to describe a board's E_{dyn} using year ring width, cambial age, axial position, and mixture type as explanatory variables. They found a significant (*p*-value 0.006) impact of mixture on stiffness. Their dataset with 1907 boards was more than four times as large, although the 407 specimens used in the present study were representatively selected from those boards. In the present study, stiffness was measured using both $E_{t,0}$ and E_{dyn}. E_{dyn} reflects an average timber quality, whereas $E_{t,0}$ (and $f_{t,0}$) represents a local property of the weakest point of the board. The so-called length effect may influence the impact of mixture on timber quality indirectly (Rais and Van de Kuilen 2017) as it increases the strength variation at board level (Table 4). A general aspect becomes apparent by the analysis. It seems to be difficult to establish a general link between silvicultural practices and wood quality. Wood quality, here defined as good mechanical properties, is not only governed by the assessment level (standing tree, log, sawn timber), but also by the type of wood parameter that is measured, and the type of statistics chosen. Whether the selection was made along a site or a forest management gradient, whether the sampling included boards from the complete tree, or whether boards came from trees of various ages, may have an impact on the variation of wood properties. It is even more relevant for future research that intends to combine forest management and wood quality that any researcher analyzing mechanical timber properties should consider sampling and measuring in such a way that can contribute to a larger grading dataset at a later date (Ridley-Ellis et al. 2016) but is also robust for changes in methods to declare characteristic values for design purposes (Stapel and Van de Kuilen 2013, 2014).

The dataset for the derivation of the initial machine settings included typical lamella dimensions with thickness ranging between 24 to 38 mm and width between 100 to 160 mm. The samples A, B, and C represented timber of low-medium quality material (Table 2). The sample D—containing the main dataset of this study—represented better quality, which can already be used for strength grading lamellas for glued laminated timber. The 407 boards were taken from old trees that remained in the stands due to their quality. In other words, the majority of trees with inferior stem and crown shape were already removed earlier by thinning. As a consequence, many boards were of good quality due to high cambial age. On the other side, all boards from logs were taken, in particular also boards close to the pith with a low cambial age. Boards from mixed stands with pine and oak increased the share of low quality timber in the sample. In total, a strength distribution of medium strength and of high variation was observed. In contrast, data recorded in other projects from Switzerland (Bacher 2014; Ehrhart 2019), Slovenia (Fortuna et al. 2018) or Germany (Frese and Riedler 2010) showed high-quality characteristics (see Rais et al. 2021, Table 1).

As it was not the main goal to compute models and settings here, threshold values were calculated straightforward with a simplified approach. Hence, threshold values derived based on the more complex approach according to EN 14081 might differ from the values derived here. The use of the cost matrix and sub-sampling method should tend to increase the threshold values, but the relative deviations found for different mixtures and combinations are likely to remain. Slightly different settings might cause some minor changes in the characteristic strength values due to the sensitivity of the 5th percentile on the strength distribution and the number of specimens. By choosing the parametric approach independent of the sample size, this effect was minimized as each mixture type contained approximately 80 boards before grading. According to EN 14358, the use of a parametric approach is mandatory for random samples smaller than 40.

For all combinations of DT-classes, the tensile strength was critical when deriving the threshold values. As the shape of the strength distribution between the mixture types changes, as may be observed on the arithmetic mean and variation in Table 5, yields and characteristic strength values are affected. The grade determining properties $E_{t,0,mean}$ and ρ_k were outperformed in all classes and combinations by on average 20% and 15% for $Model_{simple}$ and 12% and 12% for $Model_{complex}$ (Fig. 2). As mentioned by Frühwald and Schickhofer (2005) and Kovryga et al. (2020), considering the high variation in characteristic density in European hardwood species, the separate declaration of density independent of the strength class assignment would be the best preferable option for more efficient utilization of the material properties. This also is in line with findings that density variations within a single species have a negligible effect on the load carrying capacity of timber joints made with that species, as shown for spruce, beech and ekki (*Lophira alata*) in Sandhaas and Van de Kuilen (2017). Comparing the ratios between assigned and required characteristic value of $E_{t,0,mean}$ based on $Model_{simple}$ and $Model_{complex}$ (Fig. 2) showed that for one and the same wood species different ratios were possible depending on the grading method.

The reduction in timber strength variation for safe engineered timber structures requires a good grading model. Grading of beech timber with E_{dyn} as a single predictor showed promising results to estimate bending strength (Brunetti et al. 2020) or stiffness and strength based on the log's E_{dyn} (Rais et al. 2020a; Plos et al. 2022). The tensile strength prediction values achieved were high compared to Ehrhart et al. (2018), who obtained an r^2 value of only 0.16 for a high quality beech timber between strength and E_{dyn}. The differences could be clearly attributed to the different qualities, as wood in the current analysis comprises a variety of qualities allowing a broad variation and covering a bigger scatter in properties. The knot cluster

DAB together with E_{dyn} showed a high correlation coefficient comparable to softwoods. The model showed similar regression coefficients across the different mixture types. The difference in the correlation coefficients could have its cause in the different coverage of wood qualities within the mixture types. In any case, strength class DT50 could be identified as feasible, especially for boards from pure beech forests. There seems to be the potential of producing high quality beech timber with a powerful grading model. Compared to $Model_{simple}$, the grading with $Model_{complex}$, despite of only an increase of 6% in prediction accuracy, allowed to achieve significantly higher yields to the higher grades, particularly by over 10% higher yields to DT50. As shown in Fig. 5 and Fig. 6, the settings were more robust, leading to lower deviations from the desired quality (strength) level. A powerful strength prediction method was shown in Rais et al. (2021) based on a 3D interpolation of fiber deviation data from surface scans.

The analysis showed that especially beech lamellas from the mixed beech-pine stands were different from lamellae from the pure beech stands exhibiting lower yields, but also lower characteristic strength values of graded wood. The results pointed out that the silvicultural origin of trees reflected the characteristic strength values. For pure beech stands, this resulted in a higher strength class assignment. Furthermore, the differences were more pronounced if the grading model was rather simple including only one single strength predictor such as E_{dyn}. This appeared to be reasonable, as the quality differences attributed to the observable biological or structural characteristics, such as knots, remained undiscovered and overlapping effects of silvicultural treatment remained undetected. With the original sampling plan applied here, these differences could be clearly attributed.

Knowing the effects of the specific silvicultural treatments (Pretzsch et al. 2021) in the past and at present for European beech, but also for other less studied species, is an important step to efficient material utilization. It can serve as a guideline for the forestry management, or for sawmill management to attribute standing trees to the desired quality correctly. By adjusting the material supply, a more efficient material production chain and utilization can be achieved. The origin of timber, the variation within a single log (radial or longitudinal) or silvicultural treatments, all contribute to the variation in mechanical properties observed in a single sawmill, which can be particularly high (Ranta-Maunus and Turk 2010; Kovryga et al. 2017). The high variation is counteracted by temporally and/or spatially distributed sampling to obtain a representative dataset for the determination of characteristic values. However, such a procedure does not account for the initial reasons for the different wood qualities. As shown here, and despite the fact that logs were of similar dimension and age, considerable differences in mechanical properties arise from simple wood species mixture in the forest, and can be rather large especially for the highest grade. Such variation should be accounted for in case of initial settings derivation for grading machines, as it would allow to determine reliable settings, attributed to the known quality differences, without relying on coincidence. The different mixtures should be accounted for to the same extent as the wood from this mixture is actually used for sawn timber production.

Conclusion

The mixture effect on European beech (*Fagus sylvatica* L.) timber was studied with a structured experimental design, i.e., with timber sawn from logs coming from the different mixtures and other factors were *ceteris paribus*. This could be achieved by producing timber from logs of similar age/size, same position of timber inside the log and wood coming from the same area with very similar site conditions. On the basis of the research, the following could be concluded:

(1) Mixture of beech with other wood species affected the mechanical properties. The differences were observed on the mean and characteristic values of grade determining properties of both ungraded and graded timber. In the current paper, beech boards coming from the pure stand showed the highest mechanical property values and highest yields to the highest class.
(2) The mixture effect was less evident for the strength class with lower requirements in case of grading to two classes in one run compared to grading to the same class in one run.
(3) For the grading with $Model_{complex}$ comprising E_{dyn} and DAB, the differences between the mixtures regarding the mechanical properties were less evident compared to a model based on E_{dyn} only.
(4) The prediction model using E_{dyn} and DAB showed a high r^2 value of more than 0.6 (for all wood qualities used in this study originating from different forest stands) and allowed an assignment of beech timber to strength classes of up to DT50 with considerable yields.
(5) The ratios between the $f_{t,0,k}$ and $E_{t,0,mean}$ match the profiles (ratios) of tensile strength classes for medium-density hardwoods (DT-classes) proposed by Kovryga et al. (2020).

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Data availability The datasets generated during the current study are not publicly available due to confidentiality but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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