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Roundwood pre-grading with longitudinal acoustic waves for production of structural boards

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Abstract The assessment of timber quality at any stage of the production chain promises to be an advantage for the forest and timber industry. This paper presents results of wood pre-grading by means of the dynamic modulus of elasticity, which was performed along the complete processing chain—from standing trees to sawn timber. The measurements were conducted on 154 forty-year-old trees of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) from two forest experimental stands in Southern Germany. Long logs of about 13 m were bucked into short logs of 4.1 m; the dataset contained 1,820 boards cut out of 332 short logs. Pre-grading was performed at different levels: standing tree, long log, and short log. The boards were machine strength graded by a ViSCAN-COMPACT grading machine. The investigation showed high correlations between different stages in the production chain of timber. For strength classes C24 and C30 an increase in yield of about 10 percentage points by rejecting the 25 % worst logs (short or long) was observed. It did not matter if pre-grading was realized at the stage of long logs or short logs. However, methods of pre-grading at standing tree must be improved to obtain reliable prediction of dry sawn timber quality of managed forest stands ($r^2 = 0.17$).

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Vorsortierung von Rundholz mittels Längsschwingungsverfahren im Hinblick auf die Herstellung von Brettlamellen

Zusammenfassung Die Beurteilung der Holzqualität in jeder Phase der Produktionskette verspricht für die Forst- und Holzindustrie einen Zugewinn. In diesem Artikel wird eine Untersuchung vorgestellt, bei der vor wichtigen Produktionsschritten das Holz an Hand des dynamischen Elastizitätsmoduls (MOEdyn) sortiert wurde: vor der Fällung, vor dem Einschnitt und vor der Trocknung. Als Material standen 154 etwa 40 Jahre alte Douglasien (*Pseudotsuga menziesii* [Mirb.] Franco) zur Verfügung, welche von zwei Versuchsflächen in Süddeutschland stammen. Nach der Fällung wurden die Bäume auf etwa 13 m abgelängt, dann in 4,1 m lange Bloche geteilt. Aus 332 Blochen wurden 1820 Schnitthölzer eingesägt. Eine Vorsortierung geschah am stehenden Stamm, beim Langholz und bei Blochen. Die Festigkeitssortierung des Schnittholzes wurde maschinell mit einer ViSCAN-COMPACT-Sortiermaschine durchgeführt. Eine lineare Regressionsanalyse erbrachte eine hohe Abhängigkeit zwischen Rundholz und Schnittholz. Die Ausbeute für C24 bzw. C30 stieg um circa 10 Prozentpunkte, wenn ein Viertel der schlechtesten Stämme vorher aussortiert wurde. Es spielte keine Rolle, ob die Vorsortierung auf der Stufe des Langholzes oder der Bloche durchgeführt wurde. Methoden der Vorsortierung am stehenden Baum allerdings sollten noch verbessert werden, um zuverlässige Vorhersagen über die Schnittholzqualität von bewirtschafteten Waldbeständen zu erhalten ($r^2 = 0, 17$).

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1 Introduction

In Germany more than half of the harvested softwood goes to sawmills (Weimar 2011), and most of it is used for structural applications (Hapla 1980; Sauter 1992; Glos et al. 2006). Assessing the quality of wood throughout various stages of the production chain gets more and more important (Fig. 1). As quality of sawn timber may show large variations, quality assessment along the production chain may improve efficiency. As wood quality depends on many factors (genotype, kind of species, site conditions, silvicultural treatment, sawing pattern, log size, distance to the pith, etc.) it is relevant to find parameters that can be easily measured and used for quality assessment. In terms of quality of structural timber, minimum requirements for strength (bending or tension), modulus of elasticity and density are decisive for strength class assignment.

In recent years there have been tendencies to pre-grade timber earlier in the process and not only after the boards were cut from the logs. The assessment of log quality helps to sort the wood resource prior to processing. This information provides a more effective usage of timber. If a non-destructive procedure is established for grading and sorting of logs, significant savings of time and money can be realized and potentially valuable wood waste can be reduced (Jang 2000). For example, by excluding logs with low modulus of elasticity, sawmills could avoid production of low quality structural timber (Edlund et al. 2006). As wood drying is responsible for up to 50 % of the energy input during the conversion from logs to dried sawn structural timber (Puettmann et al. 2010), these costs can be reduced when only timber is dried that is suited for structural applications.

Physical and mechanical properties of timber and wood-based materials can be non-destructively predicted by acoustic tools. Detecting the dynamic modulus of elasticity (MOEdyn) of timber is a common way of machine based strength grading (Görlacher 1984; Oscarsson et al. 2011). The method is characterized by easy handling and high infeed speed. Especially the strong correlation with the use and value of timber as a building material is advantageous to MOEdyn (Ross and Pellerin 1991; Larsson et al. 1998; Hanhijärvi and Ranta-Maunus 2008). Unterwieser and Schickhofer (2007) detected no change in MOEdyn for Norway spruce (calculated by eigenfrequency) above fiber saturation point for acoustic wave based machines. In contrast, ultrasonic waves showed an influence of moisture content and required a correction on the output (Unterwieser and Schickhofer 2010).

Hence, MOEdyn calculated by eigenfrequency is interesting for grading wood in general (Ross et al. 1997; Tsehaye et al. 2000; Yin et al. 2011). At the level of standing trees, technologies and devices are available to determine MOEdyn (Wang et al. 2000; Auty and Achim 2008). In this case, mostly the velocity of an acoustic or stress wave in the lower part of the stem is measured. In practise, density has to be estimated and is normally regarded as a constant value, but, depending on the technique used, also moisture content may have an influence on the predictive capacity of the method. Intensive scanning, which should improve the correlation between wave velocity and MOEdyn of logs/sawn timber, was performed by Wagner et al. (2003): They varied the longitudinal distances of the two probes and measured the trees on four faces. However they only found a small increase in the correlation between standing tree and sawn timber.

Some effort has also been put into the evaluation of wood at the stage of logs (Carter et al. 2006; Grabianowski et al. 2006; Ross et al. 1997). All of them observed a strong relationship between the modulus of elasticity of logs and the sawn timber obtained from the logs. For instance, Ross et al. (1997) examined the relationship between the MOEdyn of a log and that of the timber obtained from the log. Results of a linear regression analysis revealed that MOEdyn of logs correlated reasonably well with average MOEdyn of timber: the r^2-value was 0.82 for Eastern white spruce (*Picea glauca*) and 0.50 for Douglas-fir (Green and Ross 1997). All these investigations did not measure timber quality at each step of the processing chain; they mostly picked out only one process stage. None of them measured all the variables needed to calculate the MOEdyn based on longitudinal vibration for each level of the processing chain. In this study, timber quality is assessed at different levels: before logging, before sawing, and before drying.

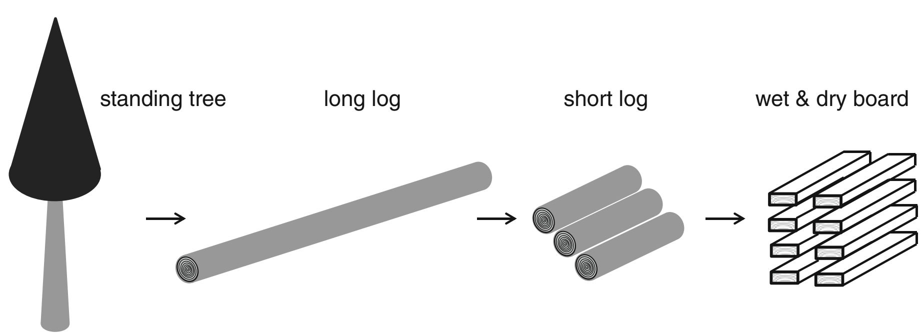

Fig. 1 Important stages of timber throughout the processing chain: from standing tree to boards
Abb. 1 Relevante Produktionsschritte einer Verwendungskette: vom stehenden Stamm zum Schnittholz

The investigation gives an overview of the MOEdyn, measured during every stage in the wood-timber production chain—from the standing tree to the sawn timber (Fig. 1). To reach this goal, a dataset of over 1,800 boards was used coming from 154 trees of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). For the current study, Douglas-fir was used as the knowledge of the recent wood quality of this species in Europe is rather low although its relevance for pure and mixed stand management in forest practice is high and increasing (Pretzsch 2003). Two questions are in the focus of the study:

(1) How strong are the correlations between the dynamic modulus of elasticity (MOEdyn) determined at the different steps tree, long logs, short logs, wet boards, and dry boards, and also between the first step and the last step?
(2) How does pre-grading at different stages of processing influence the yield of dry sawn timber?

2 Materials and methods

2.1 Material

In this analysis a sample of 154 trees of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) was used. The trees originated from two experimental plots which were part of the Bavarian network of long-term forestry research plots. One plot is located in the North of Bavaria next to the city of Aschaffenburg in the low mountain range Spessart. The other plot is located about 15 km south of the city of Ansbach. The age of all trees was about 40 years. The overall main purpose of the experiment was to investigate growth and tree development depending on growing space availability. Initial plant density differed within the plots and represented a wide range of managed Douglas-fir forests: 1,000, 2,000 and 4,000 trees per hectare. Wood quality covered the natural, recent growing range for Douglas-fir thinning trees.

The 154 trees were delimbed, topped, and crosscut to long logs of about 13 m (Fig. 2). From these long logs, 462 short logs (short $\text{logs}_{\text{original}}$) of 4.1 m length were crosscut starting at breast height (1.3 m). Using a band saw, 332 short logs (short $\text{logs}_{\text{sawn}}$) with a minimum end diameter of 200 mm without bark (the end diameter of 130 short logs was less than 200 mm) were cut into centre boards of 50 × 160 mm (n = 940) and into side boards of 30 × 100 mm (n = 490) and 30 × 140 mm (n = 390). It was tried to get as many boards as possible with the preferred cross section of 50 × 160 mm, as this is a standard cross section for the production of laminations for glued laminated timber. Table 1 gives an overview of the trees, the logs, and the

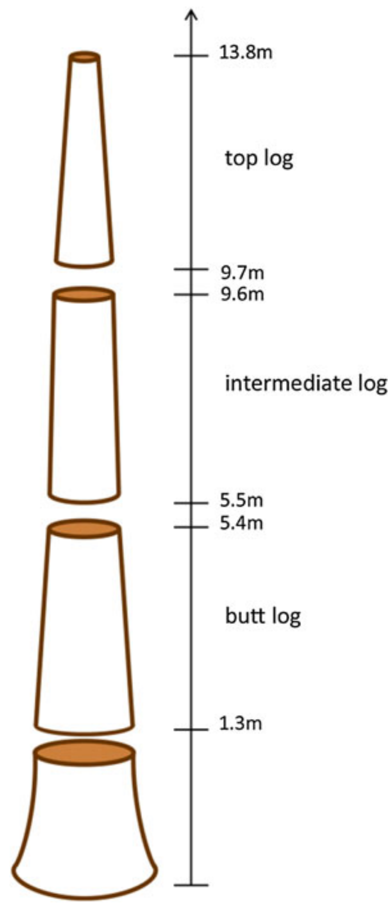

Fig. 2 Each of the 154 long logs was crosscut to short logs of 4.1 m: butt, intermediate, and top log
Abb. 2 Alle 154 Langhölzer wurden zu Blochen je 4,1 m geschnitten: Erdstamm, Mittelstamm und Kronenabschnitt

boards obtained from these logs. Mean value, coefficient of variation (COV; standard deviation divided by mean value), minimum and maximum values are given.

Mean and coefficient of variation (COV) of MOEdyn of dry boards were in line with properties of saw falling timber reported by Hanhijärvi and Ranta-Maunus (2008) and Ranta-Maunus et al. (2011).

2.2 Methods

Wood quality was assessed non-destructively by measuring MOEdyn. MOEdyn was determined on standing trees, long logs, short logs, and boards.

At standing tree level, the dynamic properties were determined using Director ST300[TM] (Fibre-gen, Christchurch, New Zealand), see also Wang et al. (2007) and Auty and Achim (2008). The time of flight was measured and the average velocity of an acoustic wave through the mature outer wood (sapwood) of the standing tree was quantified. The west azimuthal direction was chosen for the

Table 1 Details of the 154 Douglas-fir trees; sample characteristics for important parameters of different stages of the production chain: number n, mean, minimum min, maximum max, coefficient of variation COV

Tab. 1 Charakteristika der 154 Douglasienstämme; wichtige Parameter des Rund- und Schnittholzes auf den verschiedenen Stufen der Produktionskette: Anzahl n, Variationskoeffizient COV, Mittelwert, Minimum min und Maximum max

Stage	n	Parameter	Unit	Mean (COV)	Min	Max
Tree	154					
		dbh	mm	319 (0.18)	253	534
		h	m	26.4 (0.22)	21.7	33.1
		h/dbh	m cm^{-1}	0.86 (0.12)	0.55	1.08
		u	%	135 (0.10)	108	179
		v_{measured}	m s^{-1}	4,860 (0.06)	3,470	6,260
Long logs	154					
		l	mm	12,680 (0.01)	10,980	13,140
		ρ	kg m^{-3}	672 (0.09)	502	824
		f	Hz	158 (0.05)	127	182
		u	%	58 (0.27)	33	97
		MOEdyn	N mm^{-2}	10,790 (0.12)	8,200	14, 500
Short logs$_{\mathrm{original}}$	462					
		ρ	kg m^{-3}	673 (0.10)	488	856
		f	Hz	487 (0.06)	375	581
		MOEdyn	N mm^{-2}	10,750 (0.12)	7,220	14,970
Short logs$_{\mathrm{sawn}}$	332					
		l	mm	4,090 (0.02)	2,600	4,220
		ρ	kg m^{-3}	683 (0.09)	520	856
		f	Hz	481 (0.06)	383	543
		u	%	58 (0.27)	33	97
		MOEdyn	N mm^{-2}	10,570 (0.13)	7,220	14,970
Wet boards	1,301					
		ρ	kg m^{-3}	590 (0.12)	367	883
		f	Hz	517 (0.09)	369	700
		u	%	41.5 (0.27)	24.3	112.0
		MOEdyn	N mm^{-2}	10,600 (0.22)	5,020	19,290
Dry boards	1,820					
		l	mm	4,090 (0.03)	2,600	4,230
		ρ	kg m^{-3}	503 (0.09)	397	689
		f	Hz	598 (0.09)	431	1,060
		u	%	11.7 (0.28)	5	26
		MOEdyn	N mm^{-2}	12,040 (0.21)	5,800	23,490

dbh tree diameter at breast height, *h* tree height, *h/dbh* ratio between tree height and diameter at breast height, *u* moisture content, $v_{measured}$ original velocity of the acoustic wave (Director ST300$^{\mathrm{TM}}$) l length, ρ wood density, f eigenfrequency of longitudinal vibration, *MOEdyn* dynamic modulus of elasticity

measurements on the standing trees. The distance between the two probes—transmitter and receiver—was about 1 m. The Director ST300TM measured a single pass of the sound between the probes. Because the wave was initiated at a single point, the wave was considered to be a dilatational wave rather than a plane wave. Hence, the velocity was typically around 30 % higher than the velocity determined from the logs (Wang et al. 2007). For the current investigation this needs not be taken into account, because density of the standing tree was not measured and assumed to be constant. At the tree level MOEdyn is regarded as the normalized squared velocity measured by Director ST300$^{\mathrm{TM}}$ (Eqs. 1 and 2). Additionally, the moisture content and the temperature were measured. This was done by Gann active electrode MH34 and Gann Hydromette M 4050, respectively. The velocity was normalized to a moisture content of 14.5 % and a temperature of 20 °C (Unterwieser and Schickhofer 2012):

$$v_{normalized} = \frac{v_{measured}}{1.416 - 0.143 \cdot \ln(u) - 0.0009 \cdot T}, \quad (1)$$

where $v_{normalized}$ = normalized velocity, $v_{measured}$ = measured velocity, u = moisture content in %, T = temperature in °C. Even though standard reference is 12 %, the authors normalized at 14.5 % as this was the lower bound value for Eq. 1 (Unterwieser and Schickhofer 2012).

The applied non-linear moisture adjustment function (Eq. 1) is valid for timber with moisture content above fibre saturation point and temperature above freezing point. The density was not measured and therefore assumed to be a constant. Consequently, squared velocity stood in direct proportion to MOEdyn according to:

$$\text{MOEdyn} = C \cdot v^2, \quad (2)$$

where $MOEdyn$ = dynamic modulus of elasticity, C = constant, v = wave velocity of Director ST300™.

For long logs, short logs, wet and dry boards, MOEdyn was calculated according to Eq. 3.

$$\text{MOEdyn} = 4 \cdot \ell^2 \cdot f^2 \cdot \rho, \quad (3)$$

where $MOEdyn$ = dynamic modulus of elasticity, l = length, f = fundamental eigenfrequency, ρ = wood density.

Length, eigenfrequency, moisture content and density were measured. A hammer was used to excite the resonance vibration of the log or sawn timber in the longitudinal direction. The fundamental resonance frequency and its overtones were measured. The diameter of short logs was measured at the top, the middle, and at the bottom by a circumference measuring tape. Length was determined by a measuring tape. Density was defined as mass divided by volume. The mass of the short logs was determined by a load cell (measurement accuracy 0.5 % from end value). The mass of boards was determined by a balance (measurement accuracy 0.5 % from end value). Adding up volumes and mass of the short logs resulted in volume and mass of long logs. For measuring volume of boards, a vernier calliper and tape measure were used. The boards' thickness and width were measured in green and dry condition in order to account for the shrinkage. Moisture content of logs was determined according to the oven dry method described in EN 13183-1 (2002). A disc was cut out of each log, weighed, dried, and weighed again. Boards were weighed in green (wet) conditions and moisture content in green condition was recalculated using moisture content and mass in dry conditions.

Assigning timber to European strength classes can be done according to EN 338 and EN 14081-2. A machine needs to estimate bending strength, static bending modulus of elasticity, and density. In this investigation, the strength grading machine ViSCAN-COMPACT from MiCROTEC was used. This device is able to detect the density (by means of a balance), length, and eigenfrequency of boards. Additionally, moisture content was measured for each board with a GANN Hydromette RTU 600. Model and settings (ITT 98/22/07 2013) are property of MiCROTEC. The material was graded into C18 to C35 classes as given in EN 338 as these classes are the most common ones. Each board was assigned to C18 and better, C24 and better, C30 and better and C35 and better. No strength class combinations were analyzed.

Every next stage in the conversion process from trees to dry boards was correlated with the previous process stage by means of linear regression. The different stages are illustrated in Fig. 1. Statistical analysis was carried out in R statistics 2.15.0 (R Development Core Team 2012). Comparison of the means was undertaken using t-tests.

3 Results

The results are basically presented in two parts. The first part deals with the dependencies between the different stages in the production chain. The second part illustrates the effect of pre-grading on the dry board yield at different levels—standing tree, long logs, and short logs.

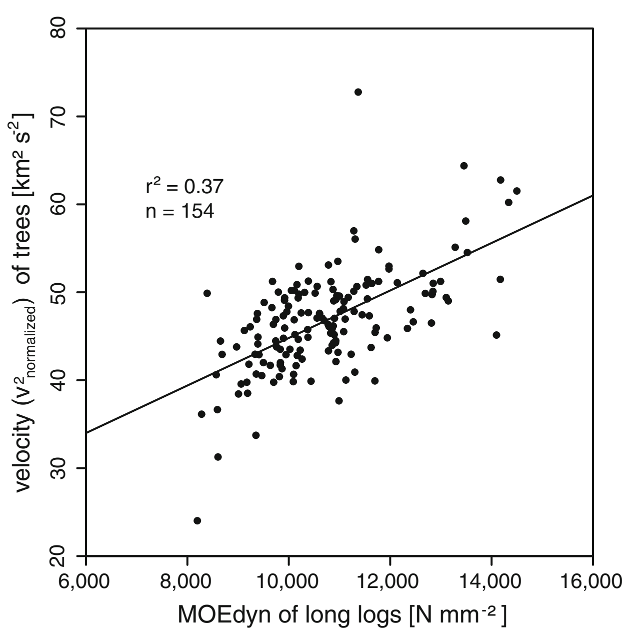

Fig. 3 Relationship between wave velocity of standing trees and dynamic modulus of elasticity of long logs coefficient of determination r^2 and sample size n of model 1 (Table 2)

Abb. 3 Beziehung zwischen der quadratischen Geschwindigkeit am stehenden Baum und dem entsprechenden MOEdyn des Langholzes; Bestimmtheitsmaß r^2 und Stichprobengröße n des Modells 1 (Tabelle 2)

Table 2 Summary of the linear regression analysis y = ax + b between the MOEdyn of different stages
Tab. 2 Zusammenfassung der linearen Regressionsanalyse y = ax + b zwischen dem MOEdyn verschiedener Ebenen der Produktionskette

y	x ($N\ mm^{-2}$)	a (±SE)	b (±SE)	n	r^2	model
Standing tree ($km^2\ s^{-2}$)						
	Long log	2.7×10^{-3} ($\pm 0.3 \times 10^{-3}$)	17.8 (±3.1)	154	0.37	1
	Butt log	2.9×10^{-3} ($\pm 0.3 \times 10^{-3}$)	17.2 (±2.6)	154	0.45	2
	Second	2.3×10^{-3} ($\pm 0.3 \times 10^{-3}$)	21.8 (±3.2)	154	0.29	3
	Top log	2.1×10^{-3} ($\pm 0.3 \times 10^{-3}$)	23.3 (±3.2)	154	0.26	4
Long log ($N\ mm^{-2}$)						
	Butt log	0.87 (±0.03)	1,671 (±323)	154	0.84	5
	Second log	0.90 (±0.03)	948 (±316)	154	0.86	6
	Top log	0.83 (±0.03)	1,568 (±385)	154	0.79	7
	Mean short logs	0.99 (±0.02)	81.0 (±214)	154	0.94	8
Short log ($N\ mm^{-2}$)						
Wet	Side boards	0.46 (±0.02)	5,401 (±192)	660	0.53	9
	Centre boards	0.59 (±0.02)	4,953 (±195)	641	0.57	10
	All boards	0.44 (±0.01)	5,979 (±139)	1,301	0.46	11
	Mean side boards	0.57 (±0.03)	4,270 (±319)	244	0.63	12
	Mean centre boards	0.76 (±0.03)	3,378 (±288)	250	0.73	13
	Mean all boards	0.69 (±0.03)	3,462 (±297)	250	0.71	14
Dry	Side boards	0.37 (±0.01)	5,809 (±167)	880	0.48	15
	Centre boards	0.44 (±0.01)	5,520 (±166)	940	0.50	16
	All boards	0.37 (±0.01)	6,098 (±118)	1,820	0.45	17
	Mean side boards	0.46 (±0.02)	4,563 (±290)	322	0.59	18
	Mean centre boards	0.61 (±0.02)	3,557 (±262)	332	0.70	19
	Mean all boards	0.59 (±0.02)	3,384 (±261)	332	0.71	20
Wet boards ($N\ mm^{-2}$)						
Dry	Side boards	0.87 (±0.01)	68 (±111)	660	0.94	21
	Centre boards	0.81 (±0.01)	253 (±73)	641	0.96	22
	All boards	0.87 (±0.01)	−178 (±72)	1,301	0.94	23

SE standard error

3.1 MOEdyn between levels of the production chain

Figure 3 shows the dependency between squared average velocity measured on the standing tree and the MOEdyn of long logs. The r^2-value was 0.37 obtained by linear regression analysis. For standing trees no density was measured. The squared average velocity was also compared with the MOEdyn of the short logs. The correlation decreased from the butt log to the top log. The coefficients of determination were 0.45, 0.29, and 0.26, respectively (Table 2).

Figure 4 illustrates the close relationship between MOEdyn of short and long logs. The r^2-value between long log and the arithmetic mean of its three short logs—butt, intermediate, and top—was 0.94. It seems that there is a very slight variation along the stem axis. When considering the dependencies between long log and single short logs, the correlation became less. The coefficient of determination was 0.84 for the butt log, 0.87 for the second log, and 0.79 for the top log.

The measurement of MOEdyn in green conditions was performed on 1,301 boards, not for all boards. These 1,301 boards were cut out from 250 randomly selected short logs; the remaining short logs passed a 3D-log-scanner and were not considered for wet grading. MOEdyn values of wet boards cut out of a short log were averaged and compared to the short log (Fig. 5). A coefficient of determination of 0.71 was obtained, which was similar to the dependency between short logs and dry boards (Table 2). This was due to the fact, that there is a very close relationship between MOEdyn measured in dry and wet condition.

Boards were sawn out of the outer part (side board) or the inner part of the log (centre board). MOEdyn values of side boards were higher than those of centre boards (Fig. 6). This difference was significant (p value <0.001). The relation between centre boards and short logs was

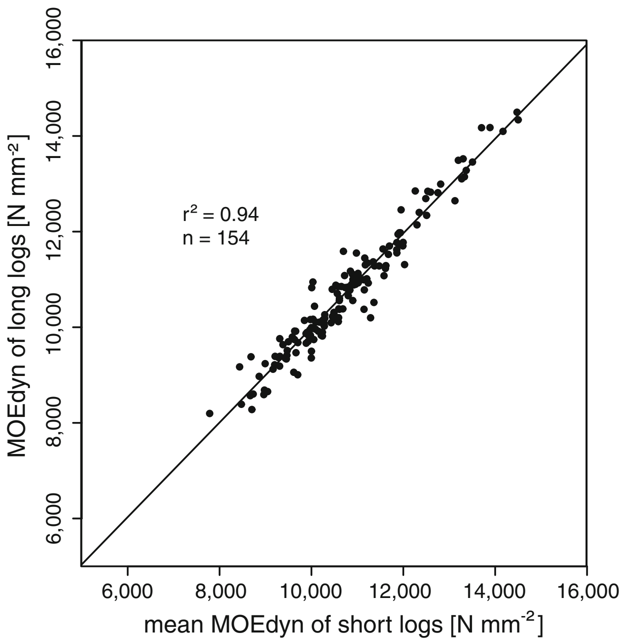

Fig. 4 Relationship between MOEdyn of long logs and their short logs cut out of them; coefficient of determination r^2 and sample size n of model 8 (Table 2)

Abb. 4 Beziehung zwischen MOEdyn des Langholzes und seiner Bloche; Bestimmtheitsmaß r^2 und Stichprobengröße ndes Modells 8 (Tabelle 2)

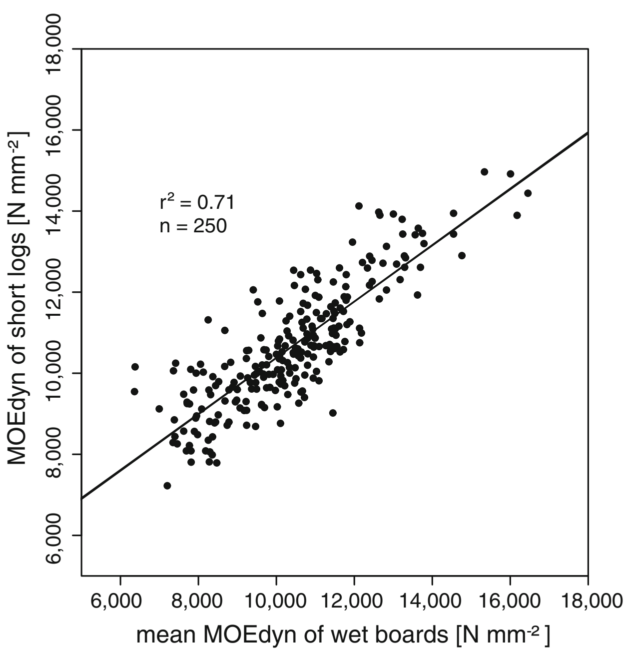

Fig. 5 Relationship between MOEdyn of the short log and its wet boards sawn out of them; coefficient of determination r^2 and sample size n of model 14 (Table 2)

Abb. 5 Beziehung zwischen MOEdyn des Bloches und seiner nassen Bretter; Bestimmtheitsmaß r^2 und Stichprobengröße n des Modells 14 (Tabelle 2)

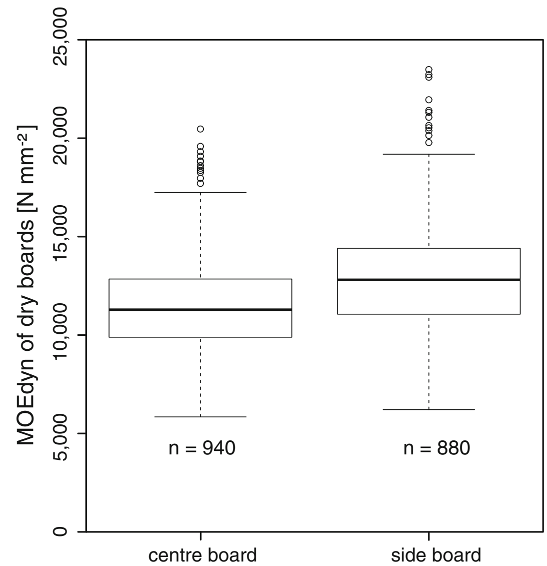

Fig. 6 Difference of MOEdyn between centre and side boards is significant (p-value <0.001). The *box* defines 25 and 75 %-quantiles. The extent of the whiskers is 1.5 times the width of the *boxes* starting from the median

Abb. 6 Unterschied von MOEdyn zwischen Haupt- und Seitenware ist signifikant (p-Wert <0,001). Die Box definiert sich über die 25 und 75 %-Quantile. Die Whiskers entsprechen dem 1,5fachen des Quartilabstands vom Median ausgehend

higher than between side boards and short logs—in wet as well as in dry conditions (Table 2).

The relationship between MOEdyn measured in wet and dried conditions was very strong. For the centre boards the r^2-value was 0.96, for the side boards the r^2-value was 0.94, and for both the r^2-value was 0.94 (Fig. 7a). The histogram of Fig. 7b displays the ratio of MOEdyn between dried and green boards. All MOEdyn-values of dried boards were standardized to a moisture content of 12 %. This data did neither show a lognormal nor a normal distribution for wet and dry MOEdyn by means of Kolmogorov–Smirnov-test (p-value >0.05). In contrast, the JCSS model code for timber structures suggests a lognormal distribution for static modulus of elasticity. On average, MOEdyn in dry conditions was 18 % higher than in green conditions. Table 2 summarizes the dependencies between sequent stages in the wood production chain. Most of the independent variables were statistically significant for $p < 0.001$.

3.2 Pre-grading of trees and logs

In a last step, the effect of pre-grading of trees or logs on the actual grading of sawn timber was investigated. Firstly, the dataset was reduced stepwise by removing low-quality trees or logs (low MOEdyn). Secondly, the remaining high-

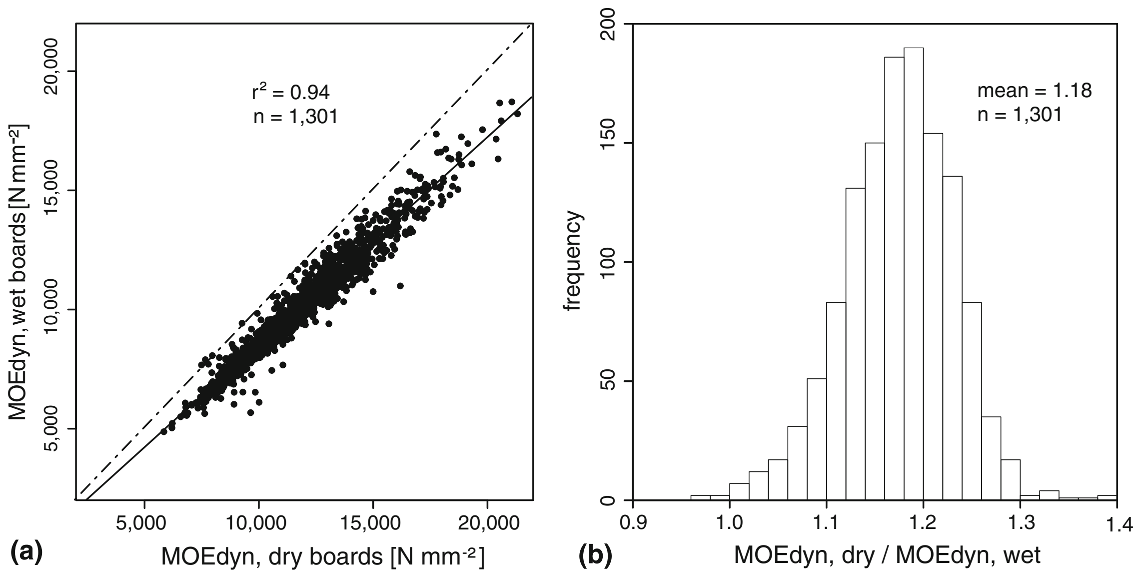

Fig. 7 **a** Relationship between MOEdyn of dry and wet boards (model 23, Table 2); **b** distribution of the ratio between MOEdyn of dry boards and wet boards

Abb. 7 **a** Zusammenhang (Modell 23, Tabelle 2) und **b** Verteilung des Verhältnisses zwischen MOEdyn der trockenen und nassen Bretter

quality trees or logs were sawn to timber, dried and then machine strength graded by ViSCAN-COMPACT. Pre-grading was conducted at the stage of standing tree, long logs, and short logs based on velocity or MOEdyn. In Fig. 8, the increase in yield is shown for different stages of pre-grading. The horizontal axis of Fig. 8 illustrates the portion of excluded logs. If no pre-grading was carried out ("no pre-grading"), the intersection with the vertical axis reflected the yield of 1,820 boards for the respective strength classes C18, C24, C30, C35 as defined in EN 338. The settings were 7,300, 10,500, 13,000, and 15,900 for assignment in C18, C24, C30 and C35, respectively. It is important to emphasize that the particular strength classes were not part of a strength class combination, which means that every single grade was graded individually.

An increase in yield for each strength class was observed. Throughout all strength classes a slight difference occured between pre-grading of long logs or short logs (crosses and triangles in Fig. 8a). For strength class C18, the yield without pre-grading was very close to 100 %, so there was no benefit in pre-grading trees or logs. On the other end of the spectrum—for strength class C35—considerable differences between the three pre-grading options were observed even when the number of trees was reduced at least by half. Reducing the sample size by the worst quarter of trees (logs), yield of dry boards rose by 3 to 10 %. This applied to all three pre-grading levels (standing trees, long logs, and short logs). When the sample size was reduced by the worst 75 % logs and only the best 25 % of logs were sawn, the yield of boards increased by more than 15 % points. This means—in absolute numbers—104 of 439 boards were strength graded in C35, instead of 135 of 1,820 boards without pre-grading logs (long logs). Avoiding 75 % of sawing and drying costs, the board number in the highest class was still 70 % of the original board number in this class without pre-grading. Obviously, in practise a market for the rejected logs is needed, but it is also clear that for high-quality sawn timber pre-grading can make economic sense.

When pre-grading logs the highest increase in yield was obtained for grades C24 and C30. Already an exclusion of the lowest 10 % of logs (short or long) improved the yield by five percentage points. Pre-grading of standing trees also led to an increase in yield by two percentage points. A reduction of trees (logs) by half raised the yield of C24 to about 85 % (standing tree) and 90 % (long and short logs). This means an increase in yield of up to 20 %.

The linear regression analysis between the stage of pre-grading and dry boards yielded the lowest relationship for pre-grading standing trees ($r^2 = 0.17$, Table 3). This went in line with the results shown in Fig. 8. No substantial difference in yield was found between long logs and short logs (Fig. 8). The r^2-values were 0.46 for long logs and 0.45 for short logs, respectively. The r^2-values increased substantially when first the mean value of all dry boards cut out off the standing tree (model 25), the long log (model 27) and the short log (model 29) was calculated and secondly related to the according level of pre-grading.

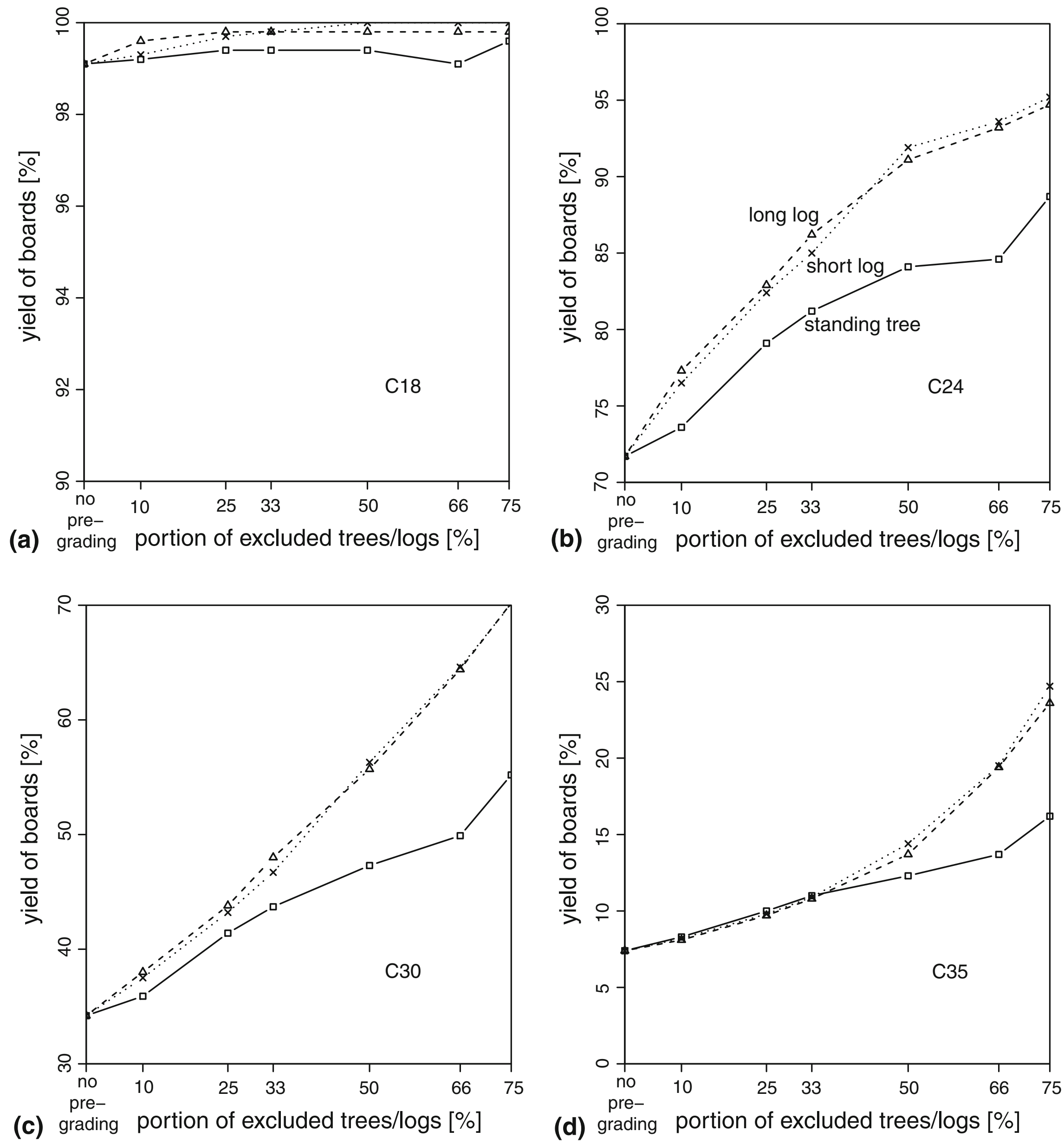

Fig. 8 Increase of sawn timber yield with increasing portions of excluded logs—depending on level of pre-grading and strength class (**a**–**d**)
Abb. 8 Steigerung der Schnittholzausbeute durch Ausschluss der schlechtesten Stämme—in Abhängigkeit der Stufe der Vorsortierung und der Festigkeitsklasse (**a**–**d**)

4 Discussion

4.1 Standing tree

The quality assessment for standing trees provides information which is relevant to forest management and which allows an economic value estimate before harvesting. The tree is not sawn down to logs yet, so it is not only a question of the right application or market. The relationship between the non-destructive measurement on standing trees and cut down logs was the lowest in this investigation (Fig. 3, $r^2 = 0.37$). Consequently, the relationship between normalized velocity of a tree and timber boards sawn out of it was also the lowest (Table 3, $r^2 = 0.17$). An additional analysis was performed correlating standing tree velocity and boards coming from the west orientation of 95 butt logs. From each butt log only the board was selected which was located at the western part of the tree. R^2-value in this case was higher with 0.37 (n = 95) against 0.17 for the relation between standing tree velocity and dry board

Table 3 Summary of the linear regression analysis between the MOEdyn of sawn timber (x) and the level of pre-grading (y)
Tab. 3 Zusammenfassung der linearen Regressionsanalyse zwischen dem MOEdyn des Schnittholzes (x) und der Stufe der Vorsortierung (y)

y	x ($N\ mm^{-2}$)	a (±SE)	b (±SE)	n	r^2	model
Standing tree ($km^2\ s^{-2}$)	Dry boards	9.5×10^{-4} ($\pm 0.5 \times 10^{-4}$)	35.1 (±0.6)	1,820	0.17	24
	Mean dry boards	17.0×10^{-4} ($\pm 2.1 \times 10^{-4}$)	25.8 (±2.6)	154	0.30	25
Long log ($N\ mm^{-2}$)	Dry boards	0.35 (±0.01)	6,354 (±111)	1,820	0.46	26
	Mean dry boards	0.62 (±0.03)	3,081 (±322)	154	0.79	27
Short log ($N\ mm^{-2}$)	Dry boards	0.37 (±0.01)	6,098 (±118)	1,820	0.45	28[a]
	Mean dry boards	0.59 (±0.02)	3,384 (±261)	332	0.71	29[b]

SE standard error

[a] See model 17, Table 2

[b] See model 20, Table 2

MOEdyn (Table 3). A reason for this was probably, that the time of flight measure considers only outer wood properties (sapwood close below the bark), which is the case for the tool in instruments like Director ST300™. Furthermore, time of flight was only detected within a distance of about 1 m at the lower part of the stem. Finally, density is difficult to measure and therefore density is often assumed to be constant or estimated otherwise. For instance, Lindström et al. (2009) assessed the variation in Scots pine trees by means of MOEdyn: On trees they measured the acoustic velocity with the transit-time tool FAKOPP™. On logs, the eigenfrequency and length were measured in order to estimate the MOEdyn. Their coefficients of determination between short logs and standing trees were comparable to the results of the current study (Table 1: 0.44, 0.30, and 0.26 for butt log, intermediate log, and top log, respectively). For Douglas-fir, Amishev and Murphy (2008a) found a lower r^2-value of 0.25 between velocities of about 700 standing trees and the corresponding speed in butt logs. However, they compared only the velocities and did not take into account the density of long logs. To improve the explanatory power of MOEdyn measurements on standing trees, time of flight was measured transversally or by varying the distance between the two probes (Wagner et al. 2003). Obviously, MOEdyn varies in axial and radial direction. The more constant the wood quality along the stem is, the smaller the influence of the measuring (Zhang et al. 2011). Searles (2012) investigated the influence of the season on time of flight measurements. He found out, that there is a low relationship between summer and winter standing tree velocity. Standing tree velocity of winter measurements were greater than that of summer measurements.

4.2 Long and short logs

The results of the current study exhibit, that there is no difference whether long logs or short logs are pre-graded. In both cases, pre-grading of logs led to very similar yields of dry sawn timber. This was due to the very strong relationship; the r^2-value for MOEdyn between long and short logs is very close to 1. Other investigations did not reach such good relationships. Certainly in this investigation, all important input variables of MOEdyn were considered at the log level: length, eigenfrequency, and density. Amishev and Murphy (2008b) investigated 1,400 trees of Douglas-fir; in total more than 3,000 logs were cut out of these. R^2-values were obtained in a range from 0.60 to 0.72 between wave velocity of long logs (with limbs and tops) and short logs. Dependencies presented in this paper are higher (Table 2). On the one hand, this may have to do with the fact that the logs all came from 40-year-old trees and thus age dependent properties were of similar magnitude for the measured properties. Furthermore, forestry measures have been taken during growth, which makes it possible that the natural variation was slightly reduced, leading to higher r^2-values. On the other hand, the used material covered a wide range of silvicultural plant densities of modern managed Douglas-fir forests. The coefficient of determination between short logs and boards cut out of them was 0.71 (Table 2, model 14). Comparing individual boards with short logs, the r^2-value decreased to 0.46 (Table 2, model 11). The relationship was slightly better than for other softwoods (Brüchert et al. 2011; Ross et al. 1997).

4.3 Wet and dry boards

The relationship of MOEdyn between green and dry conditions corresponded fairly well with results from Kollmann (1951), Unterwieser and Schickhofer (2007), and Oscarsson et al. (2010). For example, Oscarsson et al. (2011) investigated 108 side boards of Norway spruce. Their coefficient of determination obtained between MOEdyn in wet and dried states ($r^2 = 0.92$) matched the result of this paper ($r^2 = 0.94$). It does not matter, how much the moisture content is above fibre saturation point for acoustic wave measurements as opposed to ultrasound (Unterwieser and Schickhofer 2007). Density and eigenfrequency are influenced by moisture content, respectively, but their reverse moisture behaviour is compensated by MOEdyn-equation. For a successful implementation of acoustic wave measurements in practise, it must only be ensured that moisture content of boards or logs is above fibre saturation point, i.e. above about 30 %. In machine strength grading this knowledge is already successfully applied for boards. MOEdyn of the dry board was higher than MOEdyn of the wet board. The ratio (Fig. 7) between MOEdyn in wet conditions and MOEdyn at moisture content of 12 % was in line with Unterwieser and Schickhofer (2007). This makes it possible to calculate MOEdyn in dry conditions—based on wet conditions—without knowledge of the actual timber moisture content. The ratio also confirmed the ratio given in EN 384. Assuming a linear relationship as well as a fibre saturation point (FSP) of 30 % moisture content, an increase of 1 % by a decrease of 1 % moisture content was obtained.

5 Conclusion

In general, detection of MOEdyn is an approved method to estimate the strength of timber, which has already been established in sawn timber grading. As shown in the present investigation MOEdyn was able to assign wood at an early stage: before logging, before sawing, and before drying. Pre-grading in the forest on the standing tree is not very efficient. However, quality assessment of standing trees can be performed, but only as a rough guide. Best results for pre-grading were achieved for the stage of logs—either long or short. It seems to be possible to develop automated sorting systems based on acoustic tools for industrial (commercial) log sorting—either in the forest or at the sawmill. MOEdyn hardware could be installed on a harvester head. This allows determination of wood quality directly at the time of logging and before transporting to a sawmill. Alternatively, measurement of MOEdyn might be performed when sawmills receive logs. Pre-grading of trees or logs was not efficient when boards are needed in strength class C18 and better only, because without pre-grading the dry board yield of C18 is already 99 %. The highest increase in yield is observed for strength classes C24 and C30. The highest strength class graded was C35 and also here a considerable yield improvement was observed. The yield of dry boards improved from 7 to 25 % when only the best 25 % of logs (short or long) were sawn. Strength grading of sawn timber in wet conditions obtained the same results as in dried condition. Sawmills derive a benefit because they are able to reject low quality material before the energy-intensive and expensive drying process.

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References

Amishev D, Murphy GE (2008a) Preharvest veneer quality evaluation of Douglas-fir stands using time-of-flight acoustic technique. Wood Fiber Sci 40:587–598

Amishev D, Murphy GE (2008b) In-forest assessment of veneer grade Douglas-fir logs based on acoustic measurement of wood stiffness. Forest Prod J 58:42–47

Auty D, Achim A (2008) The relationship between standing tree acoustic assessment and timber quality in Scots pine and the practical implications for assessing timber quality from naturally regenerated stands. Forestry 81:475–487

Brüchert F, Wilhelmsson L, Mochan S, Sauter UH (2011) An integrated approach for wood quality prediction from standing tree to sawn timber. In: Divos F (Ed) Proceedings 17th International Nondestructive Testing and Evaluation of Wood Symposium, Sopron Hungary, Sep 14–16, 2011, pp 40–47

Carter P, Chauhan S, Walker J (2006) Sorting logs and lumber for stiffness using Director HM200. Wood Fiber Sci 38:49–54

Edlund J, Lindström H, Nilsson F, Reale M (2006) Modulus of elasticity of Norway spruce saw logs vs. structural lumber grade. Holz Roh- Werkst 64:273–279

EN 13183-1 (2002) Moisture content of a piece of sawn timber—Part 1: determination by oven dry method. CEN European Committee for Standardization, Brussels

EN 14081-2 (2010) Timber structures—strength graded structural timber with rectangular cross section—part 2: Machine grading; additional requirements for initial type testing. CEN European Committee for Standardization, Brussels

EN 338 (2010) Structural timber—strength classes. CEN European Committee for Standardization, Brussels

EN 384 (2010) Structural timber—determination of characteristic values of mechanical properties and density. CEN European Committee for Standardization, Brussels

Glos P, Richter C, Diebold R (2006) Maschinelle Sortierung von Brettern aus den Holzarten Lärche und Douglasie, Holzforschung München. Bericht Nr. 04511, p 134

Görlacher R (1984) Ein neues Meßverfahren zur Bestimmung des Elastizitätsmoduls von Holz. Holz Roh- Werkst 42:219–222

Grabianowski M, Manley B, Walker JCF (2006) Acoustic measurements on standing trees, logs and green lumber. Wood Sci Technol 40:205–216

Green DW, Ross RJ (1997) Linking log quality with product performance. In: Barbour RJ, Skog KE (Eds) Role of wood production in ecosystem management—Proceedings of the Sustainable Forestry Working Group at the IUFRO All Division 5 Conference. Pullmann, Washington, pp 53–58

Hanhijärvi A, Ranta-Maunus A (2008) Development of strength grading of timber using combined measurement techniques. Report of the Combigrade-project—phase 2. VTT Publications 686:55

Hapla F (1980) Untersuchung der Auswirkung verschiedener Pflanzverbandsweiten auf die Holzeigenschaften der Douglasie. Dissertation an der Forstlichen Fakultät der Universität Göttingen

ITT 98/22/07 (2013) Initial type testing report, Table 22-8—Settings for ViSCAN-COMPACT (Model given in TG1/1011/25rev)

Jang SS (2000) Evaluation of lumber properties by applying stress waves to larch logs grown in Korea. Forest Prod J 50:44–48

Kollmann F (1951) Technologie des Holzes und der Holzwerkstoffe, Auflage, 2nd edn. Springer-Verlag, New York

Larsson D, Ohlsson S, Perstorper M, Brundin J (1998) Mechanical properties of sawn timber from Norway spruce. Holz Roh-Werkst 56:331–338

Lindström H, Reale M, Grekin M (2009) Using non-destructive testing to assess modulus of elasticity of Pinus Sylvester's trees. Scand J For Res 24:247–257

Oscarsson J, Olsson A, Johansson M, Enquist B, Serrano E (2010) Strength grading of wet Norway spruce side boards for use as laminations in wet-glued laminated beams. In: Ridley-Ellis DJ, Moore JR (Eds) Proceedings of Final Conference of COST Action E53, 4-7 May, Edinburgh, Scotland, 2010. Edinburgh

Oscarsson J, Olsson A, Johansson M, Enquist B, Serrano E (2011) Strength grading of narrow dimension Norway spruce side boards in the wet state using first axial resonance frequency. Int Wood Prod J 2:108–114

Pretzsch H (2003) Diversität und Produktivität von Wäldern. Allgemeine Forst- und Jagdzeitung 174:88–98

Puettmann ME, Wagner FG, Johnson L (2010) Life cycle inventory of softwood lumber from the inland Northwest US. Wood Fiber Sci 42:52–66

R Development Core Team (2012) The R project for statistical computing

Ranta-Maunus A, Denzler JK, Stapel P (2011) Strength of European timber. Part 2. Properties of spruce and pine tested in Gradewood project. VTT Technical Research Centre of Finland

Ross RJ, Pellerin RF (1991) NDE of green material with stress waves: preliminary results using dimension lumber. Forest Prod J 41:57–59

Ross RJ, McDonald KA, Green DW, Schad KC (1997) Relationship between log and lumber modulus of elasticity. Forest Prod J 47:89–92

Sauter UH (1992) Technologische Holzeigenschaften der Douglasie als Ausprägung unterschiedlicher Wachstumsbedingungen. Universität Freiburg, Dissertation

Searles GJ (2012) Acoustic segregation and structural timber production. Thesis Edinburgh Napier University

Tsehaye A, Buchanan AH, Walker JCF (2000) Sorting of logs using acoustics. Wood Sci Technol 34:337–344

Unterwieser H, Schickhofer G (2007) Pre-grading of sawn timber in green condition. In: Proceedings of Conference of COST Action E53, 15–17 Oct, Warsaw, Poland, 2007, pp 161–166

Unterwieser H, Schickhofer G (2010) Influence of moisture content of wood on sound velocity and dynamic MOE of natural frequency- and ultrasonic runtime measurement. Eur J Wood Prod 69:171–181

Unterwieser H, Schickhofer G (2012) Einfluss von Temperatur und Holzfeuchte auf die dynamischen Eigenschaften von unsortierten Fichtenbrettern. Eur J Wood Prod 70:629–638

Wagner FG, Gorman TM, Wu SY (2003) Assessment of intensive stress-wave scanning of Douglas-fir trees for predicting lumber MOE. Forest Prod J 53:36–39

Wang X, Ross RJ, McClellan M, Barbour RJ, Erickson JR, Forsman JW, McGinnis GD (2000) Strength and stiffness assessment of standing trees using a nondestructive stress wave technique. Research Paper Forest Products Laboratory, USDA Forest Service (FPL-RP-585) 9

Wang X, Ross RJ, Carter P (2007) Acoustic evaluation of wood quality in standing trees. Part I Acoustic wave behavior. Wood Fiber Sci 39:28–38

Weimar H (2011) Der Holzfluss in der Bundesrepublik Deutschland 2009: Methode und Ergebnis der Modellierung des Stoffflusses von Holz. Arbeitsbericht Nr. 06/2011 Zentrum Holzwirtschaft Universität Hamburg

Yin Y, Jiang X, Wang L, Bian M (2011) Predicting wood quality of green logs by resonance vibration and stress wave in plantation-grown Populus X euramericana. Forest Prod J 61:136–142

Zhang H, Wang X, Su J (2011) Experimental investigation of stress wave propagation in standing trees. Holzforschung 65