Fachgebiet Holztechnologie

Strength grading of timber with regard to different grading methods

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Abstract

The subject of this thesis is a comparison between visual and machine grading methods for sawn timber. Both methods are applied to limit the variation in engineering properties of sawn timber. The obtained grading results are largely dependent on the method chosen. In addition, parameters such as species, source, and cross-section of the timber, as well as the applied grading rules also play a role. To what extent these parameters - depending on the chosen grading method - actually affect timber properties and yields is of interest for both producers and users of sawn timber. The thesis is focused on this aspect.
For analysing the different grading results, laboratory data of 16149 specimens were evaluated. The used cross-section has a major influence on the grading result. Furthermore, the used grading rule and the method applied to determine characteristic values are essential for the grading result. The origin of the timber influences the grading results of both grading methods. While the yields for machine grading are always higher than for visual grading, both grading methods are prone to fall short of the declared properties. It is recommended to adjust the normative framework as well as to regulate both grading procedures similarly.

Zusammenfassung

Gegenstand dieser Arbeit ist ein Vergleich visueller und maschineller Verfahren zur Schnittholzsortierung. Beide Methoden werden angewandt, um die Streuung mechanischer Eigenschaften von Schnittholz einzugrenzen. Die dabei erzielten Sortierergebnisse hängen wesentlich vom gewählten Verfahren ab. Daneben spielen auch Parameter wie Art, Herkunft und Querschnittsabmessung des Holzes oder die Wahl der Sortierregeln eine Rolle. Wie stark sich diese Parameter abhängig vom Sortierverfahren tatsächlich auf die Holzeigenschaften und die Ausbeuten auswirken, ist sowohl für Produzenten als auch für Anwender von Schnittholz von Bedeutung und steht im Fokus der Arbeit.
Für die Analyse der unterschiedlichen Sortierergebnisse wurden Labordaten von 16149 Prüfkörpern ausgewertet. Der verwendete Querschnitt hat bei der visuellen Sortierung einen großen Einfluss auf das Sortierergebnis. Darüber hinaus sind auch die Sortiernorm und die angewandte Methode für die Berechnung der charakteristischen Holzeigenschaften von wesentlicher Bedeutung. Die Herkunft des Holzes beeinflusst bei beiden Sortierverfahren das Sortierergebnis. Während die Ausbeuten bei der maschinellen Sortierung deutlich über denen der visuellen Sortierung liegen, werden die deklarierten Eigenschaften unabhängig vom Verfahren nicht immer erreicht. Es wird empfohlen die normativen Rahmenbedingungen anzupassen sowie beide Verfahren in diesem Zuge ähnlich zu regeln.

List of papers

I. Stapel P, van de Kuilen J-W G (2013): Efficiency of visual strength grading of timber with respect to origin, species, cross section, and grading rules: a critical evaluation of the common standards. Holzforschung: Aop. DOI 10.1515/hf-2013-0042

II. Stapel P, van de Kuilen J-W G (2013): Influence of cross-section and knot assessment on the strength of visually graded Norway spruce. European Journal of Wood and Wood Products. DOI: 10.1007/s00107-013-0771-7

III. Stapel P, van de Kuilen J-W G, Ravenshorst G J P (2011): Influence of sample size on assigned characteristic strength values. CIB W18 44-17-1. pp 419-432.

IV. Stapel P, Denzler J K, van de Kuilen J-W G (2013): Analysis of determination methods for characteristic timber properties as related to growth area and grade yield. Manuscript submitted to Wood Material Science and Engineering.

V. Stapel P, van de Kuilen J-W G (2013): Effects of grading procedures on the scatter of characteristic values of European grown sawn timber. Materials and Structures: Volume 46, Issue 9, pp 1587-1598. DOI 10.1617/s11527-012-9999-7

Contents

1 Introduction

1.1 Overview

The mechanical properties of timber need to be assessed before the material can be used in structural applications. As a consequence, the variation in the properties needs to be controlled by grading of the raw material. Timber characteristics influencing the performance are estimated visually, by machine or by a combination of the two. The prediction quality depends on the chosen methods. Knowing the differences between and within the two methods is of high interest for several stakeholders: grading machine producers, structural engineers and the sawmilling industry. The knowledge of the resulting engineering properties and of the share of useable material is useful in the marketing process of machines, design processes for buildings and managerial decisions in the industry. Besides these economic interests, effective grading procedures contribute to a sustainable use of wood.

The major part of structural timber on the European market is graded visually. While for machine graded timber European standards are commonly used, visual grading is done mainly based on national standards. The harmonized European standard for strength grading of structural timber with rectangular cross section EN 14081-1 lists some of the parameters which can influence grading results: different species or groups of species, geographic origin, different dimensional requirements, varying requirements for different uses, quality of material available, and historic influences or traditions. Substantial test programs have been carried out trying to cover these influences in order to establish machine settings and to check the applicability of visual grading standards. All major species can be CE-marked and the accessibility to the European market is given. Characteristic values for the mechanical properties and density are currently guaranteed for the material.

The current status quo in the grading scene is unsatisfactory as different requirements for machine and visually graded timber exist. This is partly caused by the history. Visual grading and corresponding rules have been used since centuries. As a next step many countries standardized these rules for wood quality. Germany, for example, has introduced its first standard, DIN 4074, in 1939. Later in this century, machine strength grading has been developed. The commercial use of grading machines started in the USA in 1963 (Hoyle 1963). Decades later, first national standards followed in Europe. Under these preconditions separate European standards have been developed for visual and machine grading that provide different rules for initial type testing and factory production control. Depending on the grading method, different characteristic values can be expected.

1.2 Grading methods

Visual grading

In order to use timber as an engineering material in an efficient way many European countries have issued visual grading rules for sawn timber. These national standards are supposed to optimise the grading results for the timber resources of the country or region, taking into account growth conditions, local preferences for certain cross-sections, silvicultural differences, and the history concerning structural applications. National strength grading rules assess, among others, the knot size, growth ring width, or (local) slope of grain and predict the abovementioned engineering properties.

Machine grading

Compared to visual grading, machines can predict timber properties more accurately. Although, visible strength reducing parameters can be detected by both methods, the accuracy of machines is higher as camera or X-ray systems determine knot sizes, shapes and locations with a higher resolution. Additional parameters such as density can be measured directly instead of being estimated only. Moreover, certain predictors such as the eigenfrequency or the (ultrasonic) time of flight are not determinable by visual

means. Generally, the prediction quality is higher for machine grading than for visual grading.
Most grading machines used today measure or estimate the MOE which is in return used to predict the MOR. The first grading machines measured the stiffness by measuring the deflection of a board which was passed flatwise through the machine (Müller 1968). This technique is, albeit in an improved version, still frequently in use throughout the world. However, grading machines used in Europe usually predict timber properties based on measurements of eigenfrequency or time of flight and density (Ranta-Maunus et al. 2011). Only a few machines record knot values to improve prediction accuracy. Gradewood, a European research project in which six grading machines were considered, showed that the highest prediction quality can be currently reached by a multi-sensor machine measuring the density, eigenfrequency and knots by X-ray (Ranta-Maunus et al. 2011).

1.3 Normative context

International ISO standards are available for testing of structural timber (ISO 13910:2005) and grading of structural timber (ISO 9709:2005, ISO 13912:2005). However, these standards are usually replaced by regional ones that are intended to cover an economic region. There are separate standards for North America, Australia, Japan or Europe for example. Different requirements for the determination of timber properties, the verification of the grading method, and technique as well as different control requirements are the rule rather than the exception. Not only test setups and control systems for machine graded timber differ between Europe and North America. The present work is focused on Europe with its grading systems, standards and structural timber properties.

Eurocode 5 (EN 1995-1-1), the European standard for the design of timber structures, requires that structural solid timber is graded according to the harmonized standard EN 14081-1. With a few exceptions, timber has to be produced in line with EN 14081-1 in order to put it on the market. The standard defines the requirements for grading, durability, and reaction to fire and also for the evaluation of conformity and the marking of timber. The focus of the standard as well as of the present work is on strength grading. Characteristic values, used during the design process, for bending strength, tension strength, compression strength, shear strength, modulus of elasticity and density are the result of a strength grading procedure. Both grading methods, visual grading and machine grading, are incorporated. While basic requirements are given directly in this standard several documents are referenced. Related to strength grading several other European Standards are important.
EN 14081 has three additional parts, EN 14081-2 to 4. These standards have replaced any existing national standards and fully cover machine strength grading. For machine grading, two different grading systems are regulated. For the so called “machine controlled” system, many initial tests are required for each type of grading machine. Based on these tests, settings for the machines are derived. These settings are valid only for timber with characteristics similar to those of the initial test and must not be changed. The second system is based on “output control”. The effort for initial testing is reduced, but to compensate for this, a more stringent factory production control is required. Adjusting the settings is possible. Today, European sawmillers prefer the machine controlled system. In part 3 of the standard, additional requirements for factory production are specified. In part 4, all available settings and requirements for machine controlled systems used to be listed. Due to the fast increase in the number of available grading machines and associated settings, ITT-reports were introduced replacing part 4 in order to satisfy industry demands.
For visual grading, national standards are still in use in Europe. They are supposed to be optimized for locally available timber, covering all different species and cross-sections used. For this reason, the aim of a single European visual grading standard is still not reached. As a consequence, many national grades are traded on the common European market. The large amount of grades forms an obstacle for trade and applications. To overcome this, reports containing structural properties derived according to EN 384 are necessary. These reports are supposed to guarantee the comparability of the national grades. For ease of trade EN 1912 lists the results of these reports and, for the major timber species, assigns the national visual grades to a European strength class (EN 338).
Thus, both visual and machine grading often lead to timber being assigned to a strength class listed in the

table of EN 338. Softwood classes and hardwoods can by distinguished by the first letter, C or D. This letter is followed by a number. The number indicates the 5th percentile value of the bending strength. C35 e.g. is used for coniferous timber with a characteristic bending strength of 35 MPa. As mentioned before, bending strength is not the only defined parameter. Several additional strength, stiffness and density values are listed in EN 338. As testing of all of these parameters is costly, only the values for bending strength, modulus of elasticity in bending and density need to be determined experimentally. EN 384 specifies the determination of the characteristic values and specifies equations for parameters that are not measured directly. For instance, the characteristic value for the tensile strength is derived from the characteristic value of the bending strength.

In order to ensure reliable and comparable results, paying attention to the calculation of the characteristic value is not enough. EN 408 specifies the test methods for the timber properties mentioned above. In addition, the determination of the moisture content, the timber size and the conditioning of test pieces is covered as all these parameters influence the measured properties of the material.

1.4 Parameters influencing timber properties

Glos (1978) summarized the most important parameters that influence the strength of structural timber and separated them into three levels.

The first level consists of parameters that have an immediate influence on the wood like genetics, nature of soil, weather conditions or silviculture. These parameters are directly and indirectly influencing the parameters of the two remaining levels.

Several parameters on the second level, namely the microscopic level, are affected: lignin content, orientation and gradient of the fibrils, cell wall thickness, fibre length and the pore volume.

On the third level the parameters describing the timber structure can be found. These are density, year ring width and the proportion of latewood. Other visible characteristics are listed on the same structural level: knottiness, fibre deviation, compression wood, resin pockets, cracks and infection by fungi or insects.

Additional information needs to be considered after processing of the logs, like the cross-section, the origin of the timber piece related to its position within the log and fibre deviation caused by the sawing process. Moreover, other parameters in the timber processing chain, e.g., age of the tree, harvesting, storage, kiln drying, can influence timber quality.

All parameters mentioned so far can be measured, but this has never been done in practice. They are either difficult to measure, time consuming or not readily available. Parameters from the second level are difficult to determine during the sawmilling process, the background from level one is usually unknown when the logs arrive at the sawmill. However, information about the origin of a log is usually available. Thus, all parameters from level one are available for grading in a very condensed form only. What remains to be used in the grading process are the origin of the log and the visible parameters of the timber piece.

On the contrary to visual grading, machines are capable of measuring more parameters by a couple of means such as cameras or X-ray which can increase the prediction of timber properties by measuring invisible parameters. A simple example is the density of a board. In visual grading, the year ring width is used as a predictor for density. Using a scale is more precise. Parameters that are currently measured by approved grading machines are the eigenfrequency, the time of flight, the weight and volume, density variations (by X-ray) or the deflection of a timber piece. When a combination of these parameters is used, the prediction capacity of a machine can be improved.

As an example of natural variation in structural properties of spruce the following figures are given:

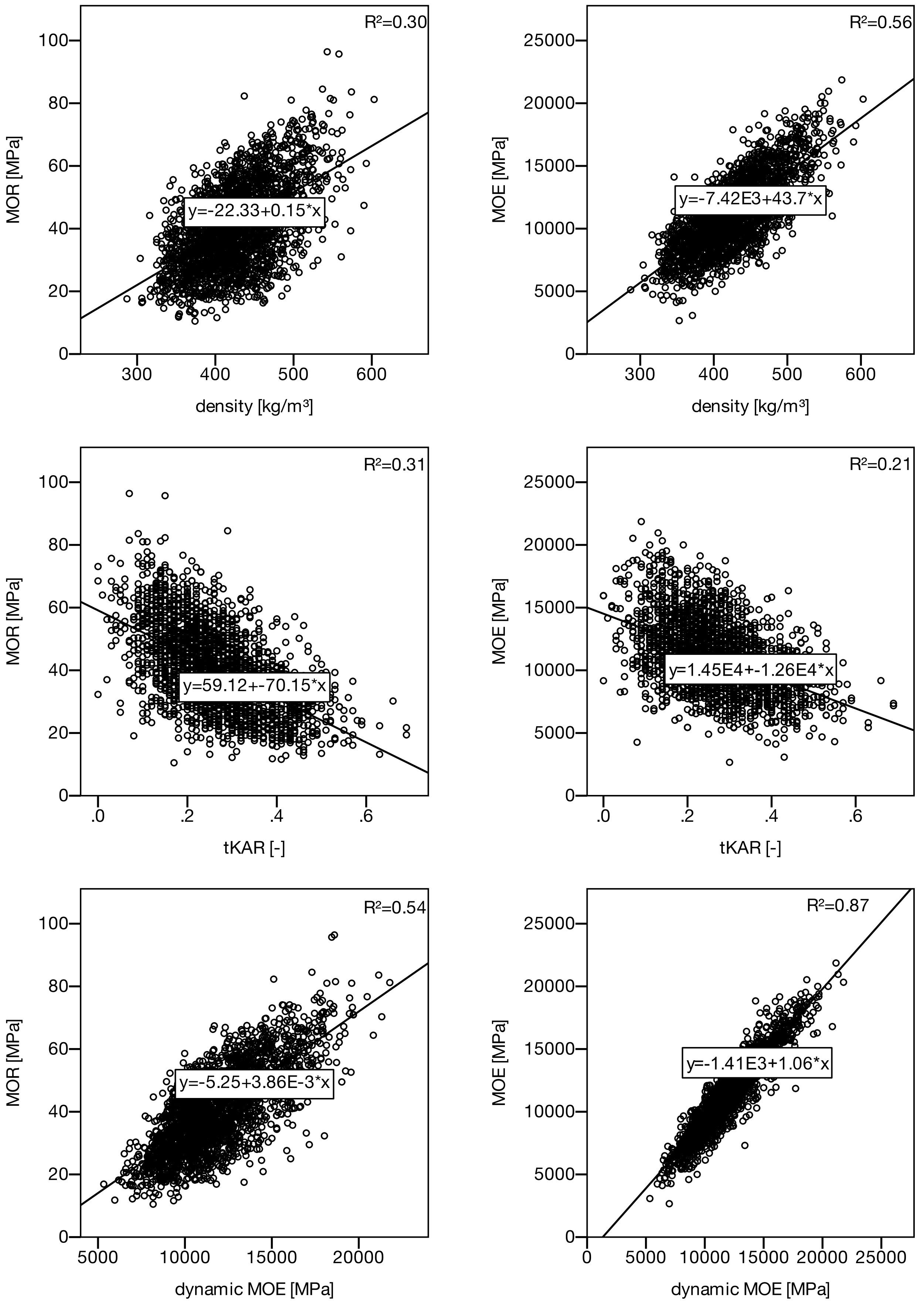


Figure 1: Illustration of the natural variation of spruce - Comparison of bending test data (MOR and MOE) to density, knot values and dynamic MOE. N = 2290.

Studies are available for many of the reported relationships. Relevant literature is discussed in the individual papers.

1.5 Objectives

The main objective of the present work is to investigate how timber properties are influenced by the grading method. In addition, parameters influencing the grading result, in terms of timber properties and economic efficiency, within one method are focused. The central problems are addressed and proposals for solution are given.
To achieve this, the following objectives have been discussed in 5 peer-reviewed papers:

I. Investigate the major European visual grading standards. Analyse how the grading results are influenced by the applied grading standard itself (i.e., quantification of knots, growth rings, etc.), the timber species, the available cross sections and the geographical source of the timber.
"Efficiency of visual strength grading of timber with respect to origin, species, cross section, and grading rules: a critical evaluation of the common standards."

II. Focus on the cross section as its strong influence on timber properties and yield is questioned. Show whether grading rules specified for the intended loading mode, bending or tension, lead to an optimised grading result.
"Influence of cross-section and knot assessment on the strength of visually graded Norway spruce."

III. Examine whether the lower permitted test efforts for visual grading lead to satisfactory grading results in terms of engineering properties. Include hardwoods in the analysis as reduced test efforts are more common for species of minor economic importance.
"Influence of sample size on assigned characteristic strength values."

IV. Analyse the influence of the geographical source on machine graded timber. Indicate geographical areas for which similar machine settings could be used. Calculate the costs for guaranteeing timber properties independent of the origin.
"Analysis of determination methods for characteristic timber properties as related to growth area and grade yield."

V. Compare grading results for machine and visually graded timber. Compare the declared and reached material properties considering safety requirements for structural timber.
"Effects of grading procedures on the scatter of characteristic values of European grown sawn timber."

2 Material and Methods

2.1 Material

The test data of 16149 specimens have been analysed for the present work (Table 1). After determining parameters which can be used for the grading procedure, all of the pieces have been destructively tested in edgewise bending or in tension parallel to the grain. Depending on the objective of the single publication different collectives were considered. While data of the major European softwood species Norway spruce (*Picea abies*) is always considered, available data from other European softwoods, like Scots pine (*Pinus sylvestris*), Douglas fir (*Pseudotsuga menziesii*), Sitka spruce (*Picea sichensis*) or Larch (*Larix decidua*) was not. European and tropical Hardwoods, European ash (*Fraxinus excelsior*), Sycamore Maple (*Acer pseudoplatanus*), black poplar (*Populus nigra*), cumaru (*Dypterix spp.*) and massaranduba (*Manilkara spp.*), are used only for paper III.

Table 1 Summary of the timber data used in the papers.

Testing			N	Data availability		Paper				
Species	Sample			Machine	Visual	I	II	III	IV	V
Bending										
Spruce	1	Gradewood	1843	x	-	x	-	x	x	x
	2	Gradewood - II	448	x	-	x	-	-	x	-
	3	TUM	75	x	x	-	-	x	-	x
	4	TUM	407	-	x	x	x	-	-	-
	5	TUM	1069	x	-	-	-	x	-	x
	6	TUM	1906	x	x	x	x	x	x	x
	7	TUM	135	x	x	x	x	-	x	-
Pine	8	Gradewood	428	x	-	x	-	-	-	-
	9	TUM	391	-	x	-	-	x	-	-
Douglas	10	TUM	157	-	x	-	-	x	-	-
Sitka	11	TUM	607	x	x	x	-	-	-	-
Ash	12	TUM	324	-	x	-	-	x	-	-
Maple	13	TUM	459	-	x	-	-	x	-	-
Popular	14	TUM	467	-	x	-	-	x	-	-
Cumaru	15	TUD	223	-	x	-	-	x	-	-
Massaranduba	16	TUD	146	-	x	-	-	x	-	-
Tension										
Spruce	17	Gradewood	1601	x	-	x	-	-	x	-
	18	TUM	665	-	x	x	x	-	-	-
	19	TUM	2555	x	x	x	x	-	x	-
Pine	20	Gradewood	873	x	-	x	-	-	-	-
	21	TUM	720	x	x	x	-	-	-	-
Douglas	22	TUM	324	x	x	x	-	-	-	-
Larch	23	TUM	326	x	x	x	-	-	-	-

Most samples were tested in the laboratory of Technische Universität München. The remaining softwood data originates from European research partners which made their data available within the Gradewood Project. Machine data is not always available, especially for hardwood and tropical hardwood (tested by TU Delft) species. Data which can be used for a rough visual classification of the specimen is available in all cases. This does not include exact knot sizes, over a longer span of the pieces, which are needed for visual grading.

Samples selection criteria are given in the individual papers and involved aspects such as availability of data (visual/ machine), cross-sectional sizes, knot sizes and locations. The samples 3 and 5 could be used in the publications III and V but were excluded from I, II and IV as the possibility that the timber was pregraded could not be ruled out. However, a verification of the data showed no noticeable deviations in mate-

rial properties when the single collectives were cross-checked against the other samples.
One specimen from sample 1 was used in III and V but excluded later due to reported problems with the MOE measurement for this specimen.
Difficulties during the knot measurement led to missing information about exact knot sizes (Visual data available) for sample 6 (1 specimen), sample 19 (2) and sample 21 (1).

2.2 Methods

In order to judge the applicability and quality of a grading method or a grading rule, the relationship between the non-destructive assessment and the destructive tests needs to be addressed. The destructive test results are characterized by bending or tension strength, modulus of elasticity and density. Additionally, information about how the datasets are grouped and about applied mathematical models is needed.

Visual Grading

Knots are the most important criterion for visual grading. Still, additional parameters have to be considered in all accepted national grading rules. These requirements are listed in Annex A of EN 14081-1.

For the majority of the specimens used in this work, all important strength reducing characteristics have been recorded under laboratory conditions. The knot sizes and positions have been determined with an accuracy of 1 mm. Knots smaller than 5 mm were not recorded. Knots are only considered in the critical test range of the specimen (Figure 3, Figure 4). In addition to knots, the recorded data covers growth ring width, the proportion of compression wood and the appearance of pith. Grading according to DIN 4074-1 in papers I, II and III is based on this information. This is also the basis for the comparison of grading standards BS 4978, INSTA 142, NF B 52-001-1, and SIA 265 in paper I, as well as for the grading of European hardwoods according to DIN 4074-5 in paper III. Differences between grading rules are partly due to knot measurements, which can be done by determining the minimum knot diameter, the knot projected on the end grain of the board, or the knot size measured parallel to the edge of the board. Not only single knots but also knot clusters are considered in all of the standards. The length of the board over which the single knots are added up to a knot cluster is, for some standards, equal to the width of the board, whereas other standards consider a common length of 150 mm. The differences between grading standards are not only caused by different ways of determining knot sizes but also because the number of classes vary. Where BS has two classes, INSTA and NF have four, not counting the reject. This fact influences the assignment of visual grades to strength classes in EN 338 as given in EN 1912 (Table 2).

Table 2: Strength class requirements for characteristic values of bending strength ($f_{m,k}$), modulus of elasticity ($E_{0,mean}$), and density (ρ_k) according to EN 338 and corresponding visual grades as given in EN 1912 for main softwood species. Paper I.

EN 338	$f_{m,k}$ [MPa]	$E_{0,mean}$ [MPa]	ρ_k [kg/m³]	DIN	BS	INSTA	NF	SIA
C35	35.0	13000	400	-	-	-	-	-
C30	30.0	12000	380	S13	-	T3	ST1	-
C27	27.0	11500	370	-	-	-	-	-
C24	24.0	11000	350	S10	SS	T2	ST2	FKI&FKII
C20	20.0	9500	330	-	-	-	-	FKIII
C18	18.0	9000	320	S7	-	T1	ST3	-
C16	16.0	8000	310	-	GS	-	-	-
C14	14.0	7000	290	-	-	T0	ST4	-

Grading of tropical hardwoods was carried out in laboratory conditions at TU Delft according to NEN 5493 and BS 5756. Visual strength grading of dense tropical hardwoods is generally restricted to slope of grain and some limit on growth defects such as knots or other growth disturbances that may be present in hardwoods.
Analysing grading rules, it can be observed that the rules are focused on the intended use of the material, on the cross-section or on a combination of these. In DIN 4074-1 different sets of grading rules for joists,

boards and battens exist. The choice of the grading rule depends on the dimensions of the timber and its intended use. How this affects the grading quality (properties & yield) is addressed in paper II.

As most of the grading has been performed under laboratory conditions at TUM, detailed knot data is available for the majority of the specimens. Although some of the research partners record the knots in a similar way this information is often hard to handle due to differences in data collection and data structure.
The information about the largest knot cluster appearing in the test range of a specimen was recorded in the same way for all specimens. From this data a parameter called total knot area ratio (tKAR) is derived. The tKAR is defined as the knot area that results from a projection of the knots on the end grain divided by the area of the cross section. Knots are considered within a length of 150 mm. Overlapping areas are only counted once. As mentioned before, based on tKAR only it is not possible to predict real grading results as all National grading rules require more than just one parameter. The tKAR information is used to analyse visual grading efficiency in papers I and V. In paper V a simple linear regression model using the tKAR value as variable is calculated to predict the bending strength:

$$MOR_{est} = 58.2 - 67.4 * tKAR \quad (1)$$

Based on the estimation for the MOR, settings are derived for a machine controlled system in accordance with EN 14081-2. These settings match settings which would result from a grading measuring only the tKAR values. Further details for the derivation of settings are given in the next section on machine grading.

In paper I tKAR is compared with grading results from national standards. This is done based on the yield values for DIN and BS. For the DIN grading, the single-knot value DEK, the most important grading criterion within this standard, is plotted against the tKAR (Figure 2). This means for DIN that those pieces with tKAR values equal or lower than 0.16 are assigned to strength class C30. Of course, the pieces in this grade are not the same as those assigned to C30 (S13) by the exact DIN grading. For the BS, the difference is smaller because the main grading parameter is the tKAR value. However, BS also specifies a margin KAR value as a second important grading parameter. This value is based on knot measurements close to the edges of the piece. To achieve a comparable yield, a number of margin KAR specimens are exchanged with tKAR specimens. Figure 2 makes the difference between DIN and BS rules obvious.

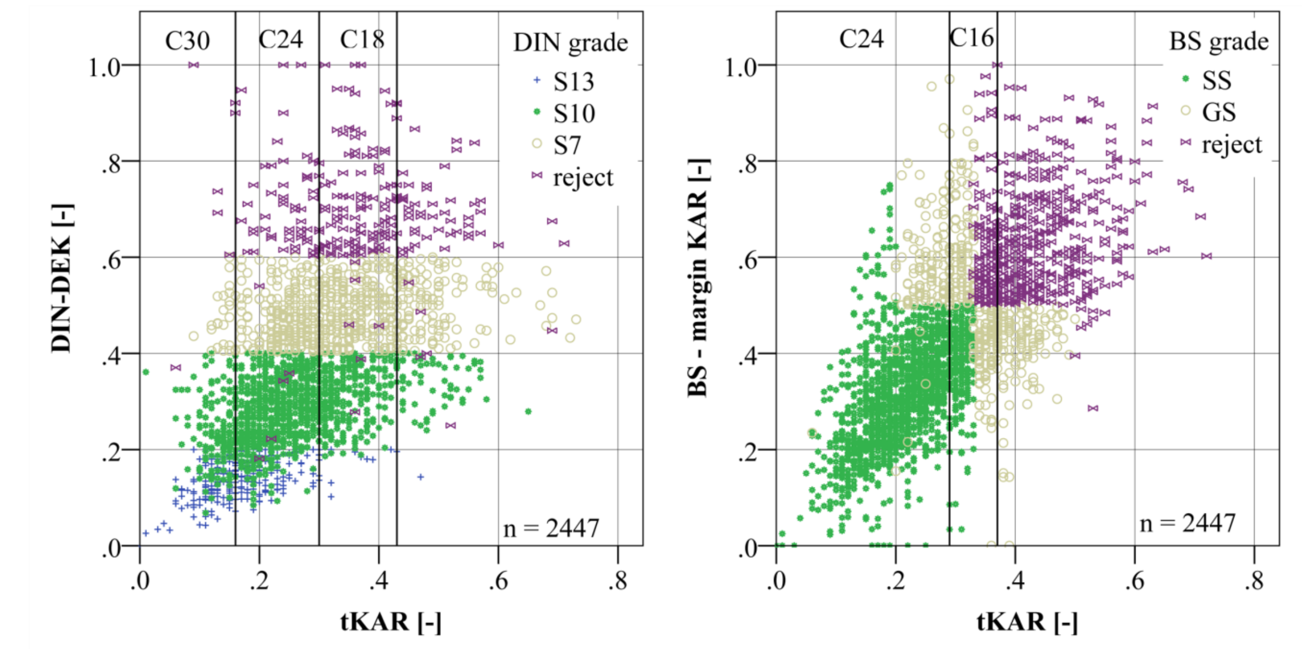


Figure 2: Illustration of the derivation of threshold values used for the grading of different sources of spruce tested in edgewise bending. Paper I.

Machine Grading

A variety of parameters can be measured by grading machines. The dynamic modulus of elasticity is the parameter which is most frequently used. High end machines do add knot data as an additional predictor.

Depending on the algorithm used in grading machine differences between the visually determined knot value and the knot value used by the machine can occur. Applying the tKAR value in addition to the dynamic MOE an accuracy is reached that is comparable to machines combining knot measurements and dynamic MOE.

The tKAR value used for machine grading was determined visually as described above. The dynamic MOE is calculated from the eigenfrequency and the density. For the frequency, the resonance frequency of a longitudinal oscillation was recorded. Based on the weight and dimension of the piece of timber, the density is calculated. As the dynamic MOE is influenced by the moisture content the value was corrected complying with the standard. In Paper IV the dynamic MOE is used as the prediction value for the MOR (MOR_{est}), the machine reading, while in paper V the MOR is predicted by considering the tKAR in addition. A linear regression model using the actual bending strength values was calculated:

$$MOR_{est} = 9.4 + 0.00334 * MOE_{dyn} - 34.4 * tKAR \quad (2)$$

The calculation of these IP (Indicating Property) values is only the first step during the process of deriving settings for a grading machine. For a so called “machine controlled” system which was used in papers III, IV and V, it is necessary to compare the IP to the test values for MOR, MOE and density. In papers III and V this was done in accordance with EN 14081-2. This method is denoted the "cost matrix method" (Rouger 1997), a risk assessment method that compares the costs of the grading results to assignments that would have been obtained by a fictitious perfect grading machine. Settings are derived for several combinations of C-classes. In paper IV settings are derived in a simpler and more fundamental way. In this paper also tension data was analysed and settings for the relevant L-classes are derived.

Testing

The destructive test procedure itself is independent of the used grading method. The timber was tested either in edgewise bending or tension. A symmetrical two point loading was used for the determination of bending strength, usually over a span of 18 times the height *h* (Figure 3). All destructive tests were performed according to EN 408. The factors k_h and k_l, used for adjusting assumed size effects, given in EN 384 were applied. The MOE value was calculated using the global MOE measurements (Denzler et al.2008) based on the total deflection of the specimen covering a length of 18 times the height. The orientation of the board in edgewise bending tests was chosen randomly.

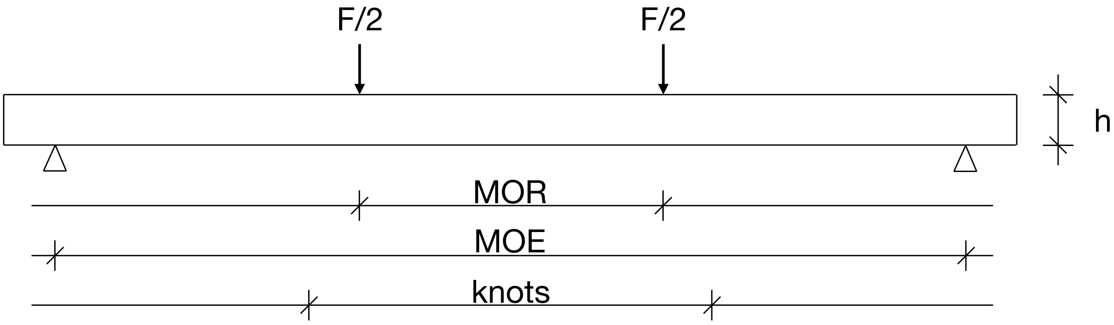


Figure 3: Illustration of the range used for the determination of the bending strength (MOR), the global modulus of elasticity (MOE) and the knots for edge wise bending tests.

For tension tests usually a span of 9 times the height is used (Figure 4). MOE is measured in the centre of the test range over a span of 5 times the height. Whenever possible the weakest section along the beam axis is tested. This requires the defect to be placed in the middle third for bending tests and between the grips for tension.

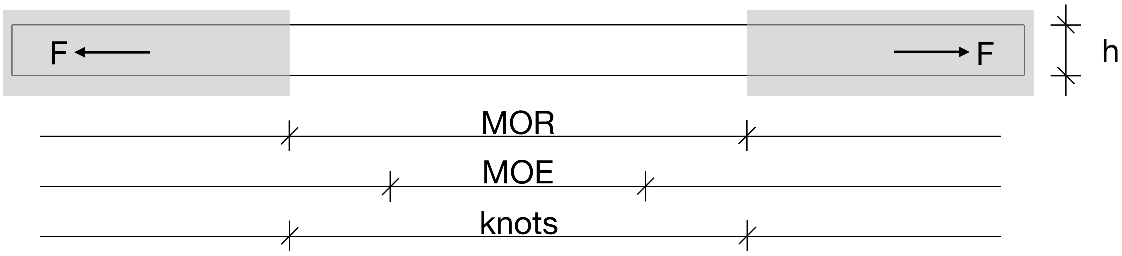


Figure 4: Illustration of the range used for the determination of the tensile strength (MOR), the modulus of elasticity (MOE) and the knots for tension tests.

Moisture content and density (ρ) measurements were carried out on small samples, free of defects and cut out close to failure location, using the oven dry method according to EN 13183-1. The resulting moisture content was used for the correction of the MOE value to the reference value set at 12% moisture content.

Secondary calculations and analysis of test data

Based on the testing results, characteristic values of the graded timber samples have to be calculated in order to allocate the timber to a strength class. For the properties of interest the characteristic value is defined as the 5^{th} percentile (MOR, ρ) or the mean value (MOE).
A number of methods is available for the determination of the mentioned characteristic values (Rouger 2004). Here, in most cases, the 5^{th} percentile is determined by using the ranking method as this is the standardized method in EN384:2010.
Paper IV deals with the influence caused by the selected determination method, studying the influence of assumed normal and log-normal distributions of the timber properties.

While the density value resulting from this calculation corresponds to the declarable value, this is not necessarily for MOR and MOE. These characteristic values which may be assumed for the timber sample are influenced by additional factors. For the calculated MOR value the factors k_v and k_s (EN384) have to be considered. A k_v-factor of 1.12 has to be applied for bending strength of machine graded timber if a bending strength below 30 MPa is reached. The factor is supposed to allow for the lower variability of machine graded timber. Whether this factor is justified is respected in paper V by evaluating material safety factors for different timber samples. The second factor k_s is less than or equal to 1 and takes the sample size and the amount of samples into account. As complementary requirements for sampling are required (EN14081-2) for machine graded timber, this factor is usually only applied to visual graded timber. k_s can reach a minimum of 0.78 if only 40 pieces are available for the calculation. This factor is in the focus of paper **III**. The average MOE value is also not directly compared to the grade requirement. A characteristic mean modulus of elasticity of bending is acceptable if it reaches 95% of the required value for a class. Although, EN338 restricts this factor to bending, it is also used for tension.

The results have been analysed separately for the type of loading, the species, the grading method, the grading standard and of course the resulting grade. Depending on the aim of the respective paper additional aspects, such as cross-section and origin were also analysed. Due to the nature of visual grading, usually considering the relative size of a knot, the cross-section is of special importance for visually graded timber. The influence caused by the origin of the timber was and is of special interest in the field of timber grading. As described above the origin of the timber has to be and is usually known. It gives condensed information about several important factors that influence timber quality. The information about the growth origin is of special interest when new grading machines shall be approved or the applicability of a visual grading standard needs to be shown. Typically, in both cases destructive tests from a representative sample are required. Since destructive tests are time consuming for machine producers and the sawmilling industry, it is often questioned how many tests are actually needed for a specific growth area. Currently, the growth area definition is linked in most cases to national borders. Although, it is recognized that the country definition is not the best solution large scale testing programs (Ranta-Maunus et al. 2011) did not succeed in overcoming this difficulty. Different approaches were chosen in papers **I**, **III**, **IV** and V to find out more about the influence from the origin on the grading results.

3 Results and discussion

3.1 Visual grading

Grading rule

The used grading standard itself directly influences the grading results. In addition to the measuring instructions the results are mainly influenced by the number of grades. The major European grading rules allow a visual classification up to strength class C30 for spruce. The British Standard is an exception. Table 3 compares the obtained characteristic properties and the resulting yield for spruce tested in bending for British (BS), German (DIN-K), Scandinavian (INSTA) and French (NF) rules.

Table 3: Visual grading results for the major European rules for spruce tested in bending. Paper I.

Rule	Strength class	n	$f_{m,k}$ [MPa]	$E_{0,mean}$ [MPa]	ρ_k [kg/m³]	Yield [%]
BS	C24	1503	25.6	12600	373	61
	C16	457	18.9	10700	361	19
DIN-K	C30	287	28.7	13200	387	12
	C24	1225	22.8	12100	363	50
	C18	697	19.1	10700	361	28
INSTA	C30	396	28.5	13500	389	18
	C24	619	25.6	12500	366	27
	C18	928	20.0	10900	359	41
	C14	210	12.8	9700	360	9
NF	C30	52	28.1	14300	373	2
	C24	763	20.5	12400	371	31
	C18	897	21.1	11500	359	37

If the grading rules given in the British standard are followed, characteristic values above the requirements are reached. For the tested dataset this is not the case for any other standard. As the resulting properties values are clearly above the requirements, the assignments can be considered safe. The main reason for this is that C24 is the highest possible grade. If the rules are applied correctly, a reject rate of 20% is reached. Due to the sophisticated and rather complicated measuring method, it is questionable if these high reject rates are actually reached in practice.

For the DIN rules for spruce tested in bending, the strength requirements are shortly missed, except for C18. The easy to use measuring principle given in the DIN standard leads to reject rates that are only half as high as those reached when BS is used. For the important commercial grades of C24 and better the yield is comparable (61% for BS, 62% for DIN). Also the characteristic values resulting from both grading rules would be very similar if the DIN standard did not distinguish between C30 and C24 but if the timber from these two grades was merged. The comparison of these two standards is of special interest as it is currently possible to use these rules for timber from the large source “CNE Europe” (EN1912: Central, North and Eastern Europe).

Spruce graded according to INSTA rules reaches the required values for C24 and C18, not for C30 and C14. Adding C14 at the bottom of available grades leads to the lowest total reject rates. However, the required strength for C14 is not reached and the share of timber graded into C24 or higher is low compared to BS and DIN. The timber graded into C14 is actually of low quality and should not be assigned to any strength class. As the used timber is mainly from Central and Eastern Europe the result for timber from the domestic area might reach the requirements. This might also be true for French timber. For the tested timber NF does not work properly. Besides, it may be doubted that the relation between knots and strength values for French timber is different compared to the rest of Europe. The yield in C30 is low, whereas yields in C24 and C18 are comparable. The application of absolute knot values as a grading criterion is unique

among the analysed standards. This is also an important reason why the yields in C30 are low compared to the other standards. The effectiveness of this method cannot be demonstrated by the resulting characteristic values. The bending strength for C24 is 20.5 MPa, whereas 21.1 MPa is obtained for C18. Hence, this standard does not seem applicable for grading timber from Central Europe.
The coefficients of variation for the different grades are normally between 0.27 and 0.30. INSTA rules lead to slightly lower cov values. NF shows the highest cov values except for the highest strength class C30 (cov 0.24). Independent of the standard, none of the visual grades shows a cov smaller than 0.24.

For other species, differences in terms of characteristic values between rules tend to be higher as the grading rules were established using mainly spruce data (Sitka spruce for BS rules).

Growth area

The influence of the growth area on the grading result is analysed for the visual method in paper I. It is checked whether the assignments given in EN1912 are correct for BS and DIN. These two examples represent the extreme as the assignment is valid for spruce originating from the growth area Central, North, and Eastern Europe. Table 4 shows the grading results analysed for Central and Eastern Europe. The required strength for C30 is reached neither for Central nor for Eastern Europe. The results show that the prediction of strength works equally well for timber from these two regions. The lower quality of the ungraded timber sample is reflected after the grading process by lower yields for Eastern European timber. Similar characteristic strength values are reached for both sources. However, density and stiffness values for Eastern European timber are far below the values of timber from Central Europe. This is primarily a problem for density as the required characteristic values for C24 (350 kg/m³) and C30 (380 kg/m³) are not reached. Analysing timber from large regions is a rather rough approach to check the geographical influence. Differences are expected to be higher if the results are analysed on smaller areas e.g. countries.

Table 4: Visual grading results for German (DIN) and British (BS) rules for spruce from Central and Eastern Europe. Paper I.

Source	Str. class	Visual standard	n	$f_{m,k}$ [MPa]	$E_{0,mean}$ [MPa]	ρ_k [kg/m³]	Yield [%]
Central Europe	C30	DIN	315	28.0	13400	390	17
	C24	BS	1186	24.8	12500	374	63
	C24	DIN	931	23.8	12100	367	50
	C18	DIN	471	17.2	10300	358	25
	C16	BS	337	18.9	10700	359	18
Eastern Europe	C30	DIN	73	28.5	11500	336	9
	C24	BS	424	23.6	11000	340	51
	C24	DIN	384	23.2	10800	342	46
	C18	DIN	289	18.0	9200	336	34
	C16	BS	200	20.0	9600	336	24

In paper V the visual grading is based on a model value using tKAR as the only prediction variable. The visual and machine grading methods are compared on an equal basis as the same method (EN 14081-2) for the derivation of settings for the single grades is chosen. Using the method intended for the derivation of grading machine settings, allows to grade timber visually up to strength class C30. However, conclusions on the level of countries are not possible as the low yield in that class leads to too few pieces for several countries.
The yield in C24 and better is high for visual grading. 79% yield is obtained for tKAR grading, 67% for DIN and 63% for BS, respectively. The 79% for tKAR is not surprising as the settings are optimized for the used dataset. While the setting guarantees that the strength requirement of 24.0 MPa for the 4893 specimens is reached, this is not the case for the single countries. The 5th percentile MOR values range between 20.9 MPa and 27.7 MPa (Table 6). Based on all sub-sample an average γ_M value, a factor considering the variation within a sample, of 2.33 is found.

Cross-section

The cross-section of the timber is an important factor for visual grading. Some standards have specific rules for certain cross-sections. DIN4074 even offers completely different sets of grading rules depending on the cross-section and the intended use. Still, even when the different sets are considered an influence from the cross-section on the characteristic properties is expected.

In paper I a direct approach to analyse the impact of the cross-section can be found. Figure 5 shows the influence of the thickness for the most important grading parameters of DIN (DEK-value) and BS (tKAR-value). The figure illustrates two facts:
1. The scatter of the different data clouds depends on the thickness. It becomes most obvious when the extremes are compared. While for smaller thicknesses high values for DEK and tKAR can be found, this is not the case for large thicknesses. At larger thicknesses large knots do not cause high tKAR and DEK values as the knot size is compensated by the larger thickness. The relative knot size is smaller for large thicknesses. Hence, only a few pieces are graded into a low grade or get rejected based on this grading parameter. As larger thicknesses have only a slightly higher average MOR value compared to smaller ones, the MOR values for high thicknesses are too low for C30. For C24 this problem does not exist as even the ungraded material reaches the required MOR value.
2. Based on the increasing R^2-values, it is obvious that with higher thicknesses the results from knot measurement rules slowly converge, even though the correlation remains low. This means that single pieces graded according to BS and DIN will be more likely assigned to the same strength class for high thicknesses rather than for small thicknesses.

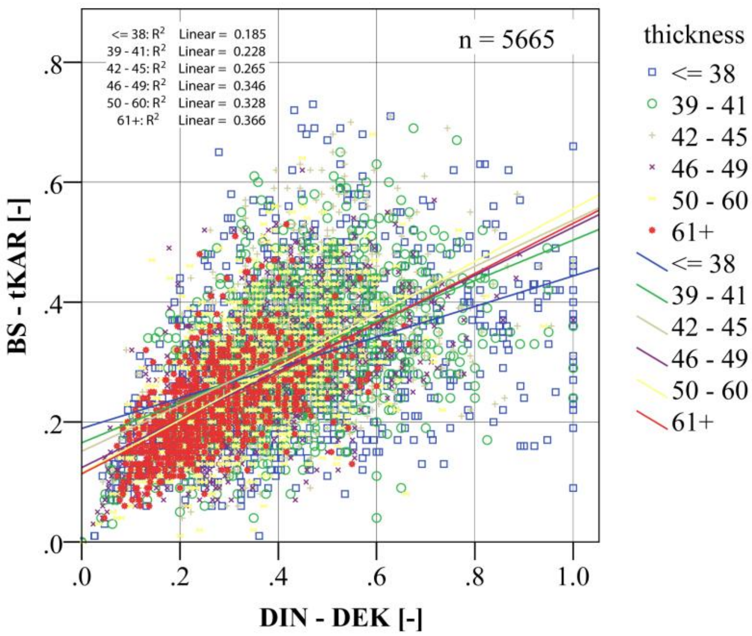


Figure 5: The influence of the thickness on the crucial grading parameters tKAR (BS) and DEK (DIN). Paper I.

An in depth analysis of the effect of the cross-section was carried out in paper II. It is limited to the German grading rules in DIN 4074-1. The DIN rule was chosen as it is applied not only in Germany, but is adopted in other national standards. It is used for the major part of graded timber in Germany, Austria, Italy, Czech Republic, Slovakia and Switzerland. More important than the countries is the fact that DIN 4074-1 gives different grading rules depending on both the cross-section and the intended use. In paper II both sets of grading rules have been analysed with regard to the cross-section. It is shown that for the joists rules the smaller dimension is more important while for the board rules the larger dimension is governing.
Figure 6 shows the trend for the strength values for different width categories. Results are given for all three grades and the ungraded timber. Dotted lines stand for the mean value, while all other elements in the figure are used for the 5th percentile values. The dashed lines are drawn at the height of 5th percentile strength given in Table 2. Thus, they represent the 5th percentile strength values resulting from the analysis for all

widths.
The highest and the lowest width class clearly show a different behaviour compared to the classes in between. Especially critical are the 5th percentile bending strength values for C24 (S10) of 15.3 MPa for the smallest widths and the low strength for C30 (S13) of 25.4 MPa for the highest class. Obviously, the grading rules do not match the challenge of very small or very large cross-sections. The reason for the low bending strength for S10 may be found in the low frequency of the appearance of knots on the edge of the joist. The reason for the low strength of large sized S13 joists can be found in the combination of maximum knot diameter and minimum cross-section of the joist together with the disregard of the pith.
Values for S7 are in the range of values of ungraded timber. Values for S10 are usually clearly above. The difference between the strength values of S7 and S10 is usually far less than 6 MPa as one would expect from the assigned corresponding strength classes C18 and C24. On the other hand, the difference between S13 (C30) and S10 (C24) is larger than expected. Not considering the values for the largest width class, the difference is between 7.8 and 15.3 MPa.

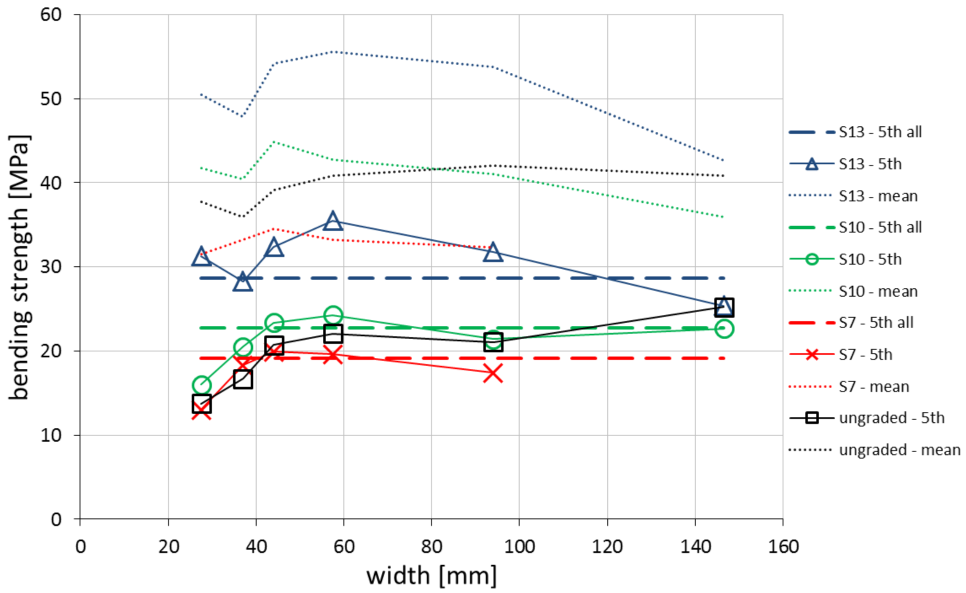


Figure 6: Bending strength for joists over width classes for different visual grades. Paper II.

The share of S7 and reject is decreasing with increasing width. This causes high shares of S10 and S13 for the larger widths. For the largest widths, a high yield in S13 is found.

Figure 7 compares the tensile strength values for different width classes. The main difference can be found for shifts in 5th percentile strength values between visual grades S10 and S13 for the different width classes. While for the small width around 100 mm, the difference between S10 and S13 never exceeds 1.0 MPa, differences up to 10.9 MPa are found for larger widths. Differences between the grades S10 and S7 for all classes are close to 1.8 MPa which is equal to the difference between S10 and S7 for the undivided dataset.

The yield for boards and joists shows a similar effect. The share of S7 and reject shrinks with growing width. The opposite trend can be observed for higher grades.

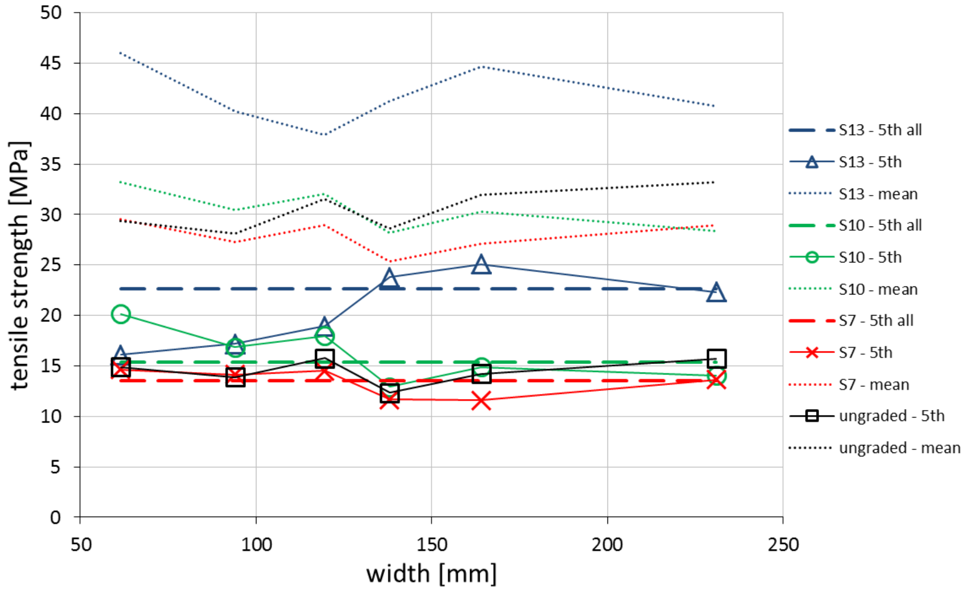


Figure 7: Tensile strength for boards over width classes for different visual grades. Paper II.

As neither the grading rule for boards nor the grading rule for joists delivers satisfying results independent of the cross-section, it is checked if the rather complicated rules for boards offer a crucial advantage. The boards used in the analysis of paper II have been re-graded using joist rules. Table 5 shows what happens. Grading results are given for the currently mandatory board rules, joist rules and the joist rules that were adjusted to allow for the different width to height ratios for boards. The last option is labelled "joist alternative".

For the joist rules, the yields for S13 are low, but with a characteristic strength of 21.9 MPa, the strength is only slightly below the requirement. For S10, the yield is reasonable and due to the low yield in S13 higher than what is obtained with the current board rules. The grading of S7 results in a high characteristic strength value of 13.4 MPa. The reject rate of 10% corresponds to the reject rate obtained for the grading of joists and is, therefore, 2% above the reject rate obtained from board rules.

The "joist alternative" rules allows larger knot ratios. What surprises, is the fact that the yield is not lower compared to board rules. On the contrary, these rules lead to lower reject rates. As the differences between board rules and the adjusted joist rules in terms of strength are small, it is questionable if the general differentiation between the grading of joists and boards is necessary. The adjusted joist rules apparently give similar yields. In practice, the differences might be even smaller as the joist rules are probably easier to apply and therefore, can lead to a more accurate grading result.

Effects caused by the cross-section do not disappear if joist rules are used for boards, yet they do not increase.

Table 5: Yields and tensile strength values for boards using different grading rules. Paper II.

rules	Grade	n	Yield [%]	MOR mean MPa	MOR cov [-]	MOR 5th MPa
board	S13	484	15	41.3	0.32	22.6
	S10	1326	41	30.1	0.36	15.4
	S7	1152	36	27.8	0.37	13.6
	reject	256	8	22.2	0.36	11.1
joist	S13	267	8	43.4	0.35	21.9
	S10	1541	48	33.3	0.34	17.2
	S7	1082	34	25.7	0.32	13.4
	reject	328	10	20.9	0.36	10.6
joist alternative	S13	645	20	40.2	0.33	22.0
	S10	1867	58	29.8	0.35	15.7
	S7	498	15	23.7	0.33	12.5
	reject	208	6	19.9	0.37	9.9

Influence of sample size

It has been shown that timber properties are strongly influenced by the grading rule, the source of the timber and the cross-section. The determined characteristic values are also influenced by the amount of pieces in the tested sample. EN 384 requires that the sample is representative for the whole population. Proof of representativeness is however difficult to achieve. For the approval tests, a minimum of 40 specimens is enough, but with the consequence of a statistical punishment (k_s-factor of 0.78). Whether this factor is adding to the reliability of declared values for visual grades is analysed in paper III. An analysis on the k_s-factor is performed, using a number of different wood species covering EN 338 strength classes from C24 to D70. It is shown that the k_s-factors used today are too high. This is especially true for sub-sample sizes close to the allowed minimum. Higher values for k_s are required in this case. Figure 8 shows that factors as low as 0.5 are required for subsample sizes of around 40 pieces.

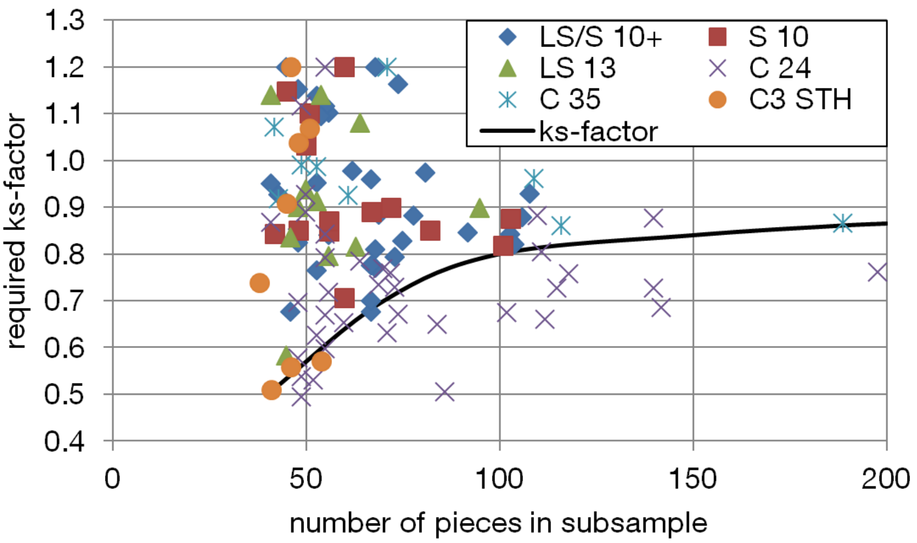


Figure 8: Suggestion for required k_s-factors in EN384 for 1 subsample. Paper III.

3.2 Machine Grading

Machine grading of timber is regulated in European standards. Hence, influences on the grading result caused by national standards can be ruled out. Depending on the parameters that are measured by a grading machine, it is possible to find effects, comparable to those caused by the cross-section, for machine graded and for visual graded timber. However, the most frequently used parameter eigenfrequency is expected to lead to stable grading results with less influence of timber size. Furthermore, in contrast to visual grading, the envisaged cross-section has to be tested during approval tests for grading machines. For these reasons, the emphasis is on the source and regulations within the European standard that are assumed to influence grading results.

Source

For the machine grading procedure in paper V, grading results for a machine measuring the tKAR value and the dynamic MOE as variables for the prediction of the bending strength have been analysed. The good prediction of the bending strength allows that grades up to C40 can be analysed. Comparisons between the results on country level are limited to C24 and C30 because a substantial amount of data for each country is needed. For both grades settings have been derived with and without the k_v-factor that reduces the required characteristic strength value for machine graded timber.

Strength values for machine graded timber for single countries can become as low as 23.3 N/mm² for C30 and 18.9 N/mm² for C24 if the k_v-factor is used (Table 6). If k_v is not applied, the 5th-percentile strength values obviously increase. The minimum for C30 in that case is 25.8 MPa. The remaining nine countries reach at least 90% of the required strength values.

Table 6: 5th percentile bending strength values for different countries. Paper V.

Grade		C30	C30	C24	C24	C24
Mehod		Machine	Machine	Machine	Machine	Visual
k_v		No	Yes	No	Yes	No
	Country					
$f_{m,k}$ [MPa]	A	29.4	26.0	24.5	22.6	25.1
	B	31.2	27.8	24.0	21.8	25.0
	C	28.5	26.5	22.3	18.9	22.0
	D	25.8	23.3	22.6	19.3	21.6
	E	31.9	27.8	27.5	24.9	27.7
	F	32.6	28.0	26.6	23.0	27.4
	G	31.6	27.8	23.9	21.2	23.9
	H	34.4	24.5	23.4	21.2	22.8
	I	27.7	25.3	22.2	21.7	21.9
	J	30.5	26.2	23.9	19.5	20.9
	All	30.0	27.0	24.0	21.4	24.0

The focus in paper IV is also on the influence that countries have on grading results. For C24 MOR values for single countries are calculated that can be compared to the results for C24-Machine-k_v-yes given in Table 6. Differences in the derivation of settings and in the grading method (using MOE only instead of MOE and tKAR) are leading only to minor deviations between the results. The minimum is 18.8 MPa instead of 18.9 MPa, the maximum is 24.2 MPa instead of 24.9 MPa.

A method was introduced to judge the applicability of settings for single sources without extensive checking for single classes or class combinations. The method compares the grading results for the undivided datasets to the results for single countries. Table 7 gives absolute and relative risk values for the countries included in the dataset. The absolute risk values show the deviation that has to be expected for the single countries. Relative values can be used to check MOR values to MOE or density. An absolute MOR value for timber from the Czech Republic (CZ) shows that we have to expect characteristic MOR values that are 2.8 MPa short of the declared values. More conservative settings would be necessary in order to reach the characteristic MOR. As no distinct setting combinations but basically all possible combinations are covered by this method, almost all sources show negative values for at least one property. Hence, slight deviations do not pose a really threat. The proposed method clearly identifies the property which can cause a problem. While for timber from the Ukraine (UA) or Romania (RO) no problems are expected for MOR values, the situation for MOE and density is different. Analogue to the risk values, loss values are given that reflect a higher potential for timber of a certain country. If this potential can actually be used has to be evaluated by considering the risk values of the same country. For example timber from Belgium (BE) shows a high potential (high loss value) for the MOR while for the MOE a considerable risk value can be found. Lower settings and higher yields should be possible if settings were derived separately for this source.

Table 7: Absolute (abs) and relative (rel) RISK and LOSS values for bending data separated for different countries. Paper IV.

Country	RISK						LOSS					
	MOR		MOE		DENS		MOR		MOE		DENS	
	abs [MPa]	rel [-]	abs [MPa]	rel [-]	abs [kg/m³]	rel [-]	abs [MPa]	rel [-]	abs [MPa]	rel [-]	abs [kg/m³]	rel [-]
AT	-8.1	-0.41	-17	0.00	-22	-0.06	0.0	0.00	339	0.03	2	0.01
CZ	-2.8	-0.14	-28	0.00	-1	0.00	0.0	0.00	74	0.01	7	0.02
DE	-2.2	-0.11	-14	0.00	0	0.00	0.0	0.00	318	0.03	8	0.02
SK	-1.6	-0.08	-445	-0.04	-5	-0.01	0.9	0.05	59	0.01	1	0.00
FR	-0.7	-0.04	-349	-0.03	-7	-0.02	1.8	0.09	70	0.01	3	0.01
SE	-0.7	-0.04	0	0.00	0	0.00	0.5	0.03	309	0.03	5	0.01
PL	-0.6	-0.03	0	0.00	-1	0.00	0.3	0.02	227	0.02	6	0.02
RO	-0.3	-0.02	-1045	-0.09	-21	-0.06	1.3	0.07	0	0.00	0	0.00
SI	-0.2	-0.01	-90	-0.01	0	0.00	0.5	0.03	73	0.01	4	0.01
UA	-0.1	-0.01	-554	-0.05	-21	-0.06	1.4	0.07	0	0.00	0	0.00
BE	0.0	0.00	-463	-0.04	-1	0.00	3.2	0.16	0	0.00	7	0.02

The calculation of the loss values is a first approach to the economic aspect of guaranteeing timber properties on country level. It becomes more concrete when the actual yield figures are considered. What happens to the yield when the requirements have to be reached on regional or country level, is presented graphically in Figure 9. The yield is always given for both methods of determination for characteristic properties, the non-parametric method according to EN 384 and the proposed log-normal distribution (labelled prEN 14358). The influence of the method will be discussed below. In a first step results according to EN 384 are discussed. The figure includes two examples, C24 and L36. The curve for each strength class starts with the yield that results from settings that guarantee that the complete datasets reaches the requirements (“EU”). Moving right, the yield is connected to settings that work for different regions (“RE”). The region which leads to the required setting is mentioned below the header “RE” (CE Central Europe, EE Eastern Europe). Yields for settings that lead to safe timber properties on country level are given on third rank including the country which is crucial for the reduction. Above the country code the number of countries for which the corresponding setting is valid can be found.

For C24 the difference between European and regional level is large. The required settings for EE lead to a decrease in yield of 6.5%. Density requirements lead to higher settings for EE. However, this could be easily avoided. Introducing an additional IP for the density would solve that problem. Without that extra IP the minimum yield, for which characteristic values could be guaranteed for all 11 countries would result in a yield for the European dataset of 81.7%. Checking the setting on the European dataset leads to a yield of 95.6% instead. This EU setting would lead to too low characteristics for timber from RO, DE, CZ, AT, UA and SK. Due to the high quality of the ungraded timber from BE, FR and SI no settings at all are required for C24. For these samples, all characteristic values can be reached without grading.

In L36 the yield calculated for the European dataset is only lower if the settings are based on timber from CH, LV, SE or CZ or DE. For all other countries higher yields are reached. The maximum difference in yield between proof on European and on country level is 18.9%.

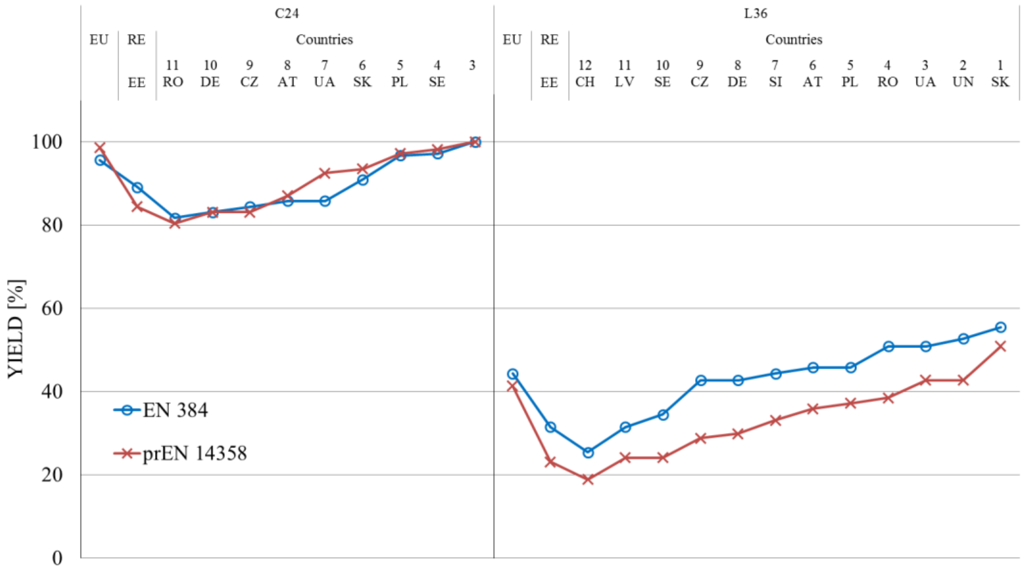


Figure 9: Yield for different strength classes depending on the source for that timber properties are guaranteed. Analysed for C24 and L36. Paper IV.

Standard

In Figure 9 not only the influence of countries is illustrated but also the influence caused by the calculation method of characteristic values. As mentioned before, it is suggested to calculate strength values no longer by using a non-parametric method, but by using a parametric approach assuming a log-normal distribution of the MOR values instead. For the two examples there is clearly a difference between C24 and L36 depending on the method. While differences between the two calculation methods for C24 are small, immense differences can be found for L36. Assuming the proposed log-normal distribution, resulting tension MOR values are low compared to the values from the calculation used today. The reason for this is that values for the coefficient of variation for tension data in the graded samples are higher. The relatively higher variation leads to lower characteristic strength when a distribution is assumed for the calculation of characteristic values instead of using only the extreme values that are used for the ranking approach. The reduced number of pieces, for the graded dataset that is separated by countries, leads to a further decrease compared to the undivided dataset (Figure 10). Here, a clear difference can only be found for the normal distribution proposed as an alternative approach for the calculation of characteristic values. Figure 10 shows the course of the MOR with increasing IP values for two strength class combinations. While the log-normal distribution promises an increase when calculating characteristic values compared to the currently used method given in EN384, this effect cannot be found for L-classes. For smaller datasets generated during the procedure of deriving settings even the MOR values for the C-classes do not increase when calculated according to prEN14358 (Figure 9).

For the two remaining properties - for that a change in the calculation method is also drafted - no differences between C- and L-classes is found. While differences between the methods are small for the MOE, the characteristic density determined in accordance with prEN14358 results in lower characteristic density values. Assuming a normal distribution for density values of in-grade timber leads to lower 5th percentile values in all cases. Although, differences for the particular settings are usually not above 10 kg/m³ this might be grade determining in single cases, especially for the density values listed in EN 338.

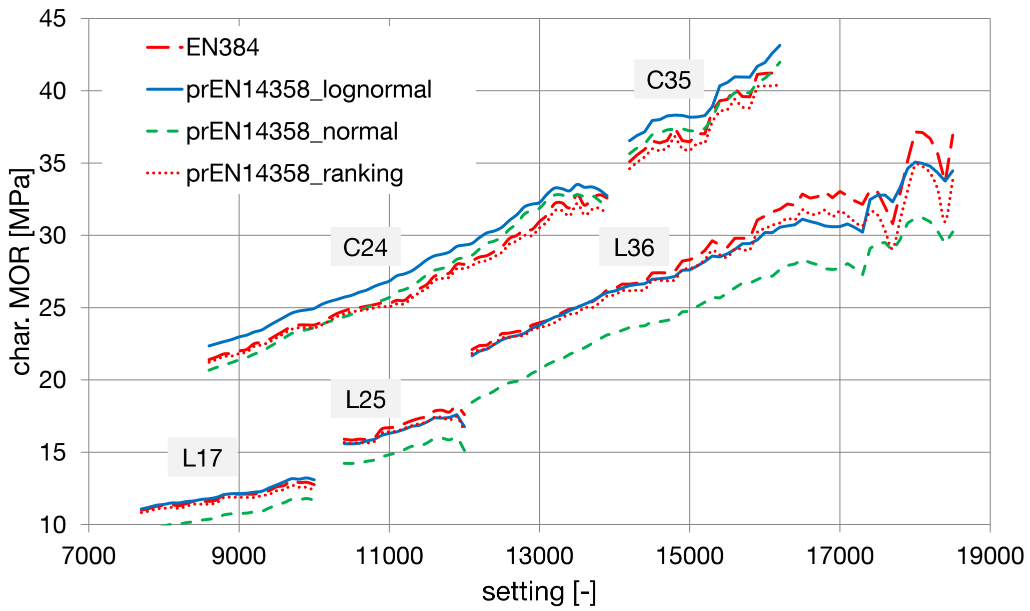
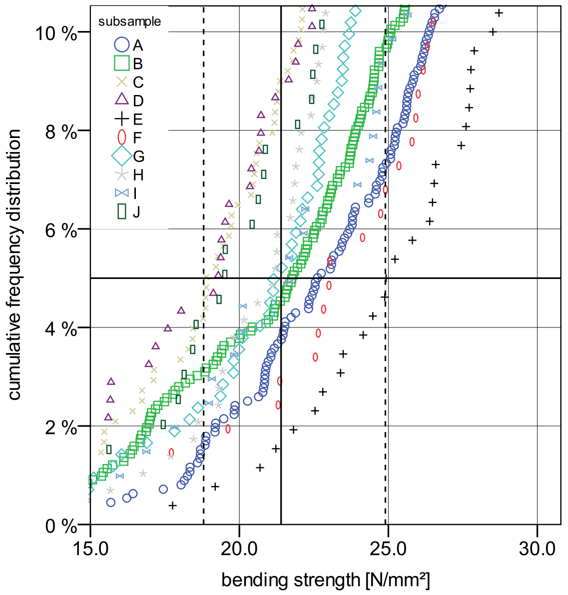


Figure 10: MOR values plotted against the settings for a strength class combination for bending and tension, respectively. A distinction is made between calculation according to EN 384 and prEN 14358. Paper IV.

EN 384 specifies the k_v-factor which has to be used for the determination of the bending strength value of machine graded timber. It is applied to class C30 and classes below. That this factor directly results in a lower bending strength for graded timber is obvious and not further surprising. However, the lower requirement on the strength has a second effect. The variation of timber in-grade properties is increasing due to the increased yield. Depending on whether a strength class is graded on its own, e.g. C24-rej, or in combination, e.g. C35-C24-rej, the variance of properties differs. If extremes for the grade C24 shall be compared the combination *C24-rej using k_v* and the combination *C35-C24-rej not using k_v* are good examples. Figure 11 and Figure 12 show how differently the lower tails of batches of C24 timber could be composed. For C24 from *C35-C24-rej not using k_v* a total of 2377 pieces are assigned to that grade, while there are 4611 pieces in C24 if C24 is graded on its own (*C24-rej using k_v*).



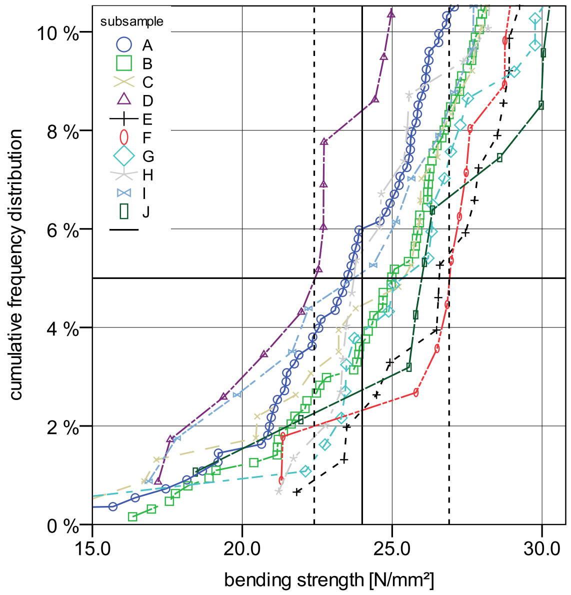


Figure 11: Lower tail of the strength distribution separated for the different countries (subsamples) - *C24-rej using k_v.* Paper V.

Figure 12: Lower tail of the strength distribution separated for the different countries (subsamples) - *C35-C24-rej not using k_v.* Paper V.

Based on the information about strength and its variation within a grade average γ_M values over all sub-samples were calculated. The calculated values for γ_M depend on the strength class. If the grading process allows for a clear separation of timber into more than two grades (e.g. *C35-C24-rej*), the coefficient of variation is substantially reduced and consequently a lower value for γ_M could be declared. Looking at the results of Table 8, the currently used γ_M -value of 1.3 for high quality machine graded timber can be justified.

Table 8: γ_M –values for machine graded timber: Averages and standard deviations calculated from the single sub-samples. Paper V.

Grade	Grade class combination	k_v	Yield	$\gamma_{M,Std}$	$\gamma_{M,avg}$
C24	C24-rej	No	4338	0.85	2.22
		Yes	4773	1.50	3.36
	C35-C24-rej	No	2339	0.15	1.45
		Yes	2377	0.16	1.45
C30	C30-rej	No	2720	0.31	1.49
		Yes	3622	1.04	2.00
C35	C35-rej	No	1391	0.19	1.28
C40	C40-rej	No	492	0.13	1.18

3.3 Comparison and evaluation of the grading methods

Deviations from declared values for graded timber occur for both, visual and machine grading. Based on timber properties and the yield a comparison between the two grading methods is possible.

Differences for strength values on country level can be big for both grading methods. Due to the lower prediction quality for visual graded timber the difference between the highest and the lowest value found for the different countries is higher. However, one can find lower absolute values for machine graded timber if the k_v-factor is used. The given reason for the existence of the k_v -value - to allow for the lower variability of f_{05} values between samples for machine grades in comparison with visual grades – cannot be confirmed. From the results of γ_M -value for strength class C24, it can be clearly seen that a positive effect of machine grading can only be obtained if C24 is graded in a grade combination with a higher grade. Otherwise, the characteristic strength of samples graded by a machine is not much better than when graded visually, neither is the coefficient of variation of the graded material influenced in a positive manner. As a consequence, the k_v-factor as currently applied cannot be justified.

Except for paper III yield figures were analysed for the different grading methods using different standards and grading parameters. Although, the datasets are not perfectly equivalent (compare Table 1) comparable yield values can be found. As a direct comparison of yield values is not done in the papers a summery is given here in Table 9. Obviously, not all listed strength classes would practically be graded in the given combinations (e.g. C40-rej, C30-rej, L30-rej). For bending, C24-rej is the most frequently used grade combination. For currently accepted grading rules, DIN 4074 shows the best performance here. Only 38% of the timber does not reach strength class C24. This yield could be increased if the theoretical visual grading procedure presented in paper V was followed. 79% of the timber could be graded to C24. For machine grading the yields are higher. Depending on whether the tKAR is used in addition to the dynamic MOE or not, the yield for in-grade timber lies between 96% and 98%. Strength classes above C35 can only be reached if machine grading is used.

Reject grades for tension grades for machine and visual grading are close together. For the popular combination L36-L25-L17-reject for machine graded timber are “only” 5% lower. The distribution of in-grade timber shows larger deviations for the two grading methods. For L36 machine grading allows a yield of 44% while visual grading does not even reach half of this value.

Table 9: Overview of yield figures for spruce.

Testing	Method	Paper	Standard or used parameter	Yield [%]						
Bending				C14	C18	C24	C30	C35	C40	reject
	Visual	I	BS 4978	-	19	61	-	-	-	20
			DIN 4074-1	-	28	50	12	-	-	10
			INSTA 142	9	41	27	18	-	-	5
			NF B 52-001-1	-	37	31	2	-	-	30
		V	tKAR	-	-	79	-	-	-	21
	Machine	IV	dyn MOE	-	-	76	-	16	-	8
				-	-	-	57	-	-	43
				-	-	96	-	-	-	4
				-	100	-	-	-	-	0
		V	dyn MOE& tKAR	-	-	-	-	-	10	90
				-	-	49	-	28	-	23
				-	-	-	74	-	-	26
				-	-	98	-	-	-	2
Tension					L17 S7	L25 S10	L30 -	L36 S13		reject
	Visual	II	DIN 4074-1 lamellas		16	56	-	21		8
			DIN 4074-1 boards		36	41	-	15		8
	Machine	IV	dyn MOE		27	26	-	44		3
					-	-	71	-		29
					-	93	-	-		7
					100	-	-	-		0

As mentioned earlier, the parameters used for the grading procedure were all recorded in laboratory. For machine grading this means that the differences to grading in practice are small. For visual grading the results in practice are expected to be different. Two major effects have to be expected. Due to an increased accuracy during the grading procedure wrong assignments become more likely. Unlike in the laboratory - where only the centre part of the board is of interest (Figure 3 & Figure 4) - the complete length of the board has to be considered for grading. This would further increase the share of timber that is graded into low grades or gets rejected. As the dynamic measurement of the MOE considers the whole length in the laboratory and in practice, no differences have to be expected here. This would put machine grading in an even better position in terms of yield. The existing large differences in yield figures between the methods give rise to the question, why visual grading is still preferred in Central Europe. It is recommended to adjust the normative framework as well as to regulate both grading procedures similarly.

4 Conclusions

The properties of graded timber are influenced by the cross-section, the origin of the timber and the applied grading standard. The four major European grading rules DIN, BS, INSTA and NF cannot be compared grade by grade, as the number of possible grades in the single standards ranges between two (BS) and four (INSTA). The application of DIN, BS and INSTA on spruce reveals that they can be used to grade the material safely except for large cross-sections above C24. An in-depth analysis of the DIN standard DIN4074-1 with special focus on the influence on cross-sections was carried out. It was shown that the graded timber properties are influenced by the timber size.
Even within the DIN standard, consistent size effects cannot be found as two sets of grading rules (for joists and boards) are provided. It is important to check the influence of timber width on the mechanical properties separately for each grade. Beyond the effect of the width, it was shown that is not necessary to have different grading rules for joists and boards. Comparable characteristic values and yields for spruce can be reached when joist rules with adjusted threshold values are applied. This would not only allow for easier grading rules, but also for higher yields.
Comparing the standards, yield differences for spruce graded in C24 and better can be found. The DIN rule gives the highest yields. Due to the possibility of assigning material to strength class C14 the lowest share of rejected timber is found for the INSTA standard.
A number of national timber grades are assigned to European strength classes in EN1912. These assignments were shown to be wrong for a number of cases. New limits for cross-sections and source areas for several listed timber species are required. In order to find reliable characteristic values for mechanical properties secure sampling and calculation methods are needed. This is currently not the case when small sample sizes are used. For each grade and species it is possible to derive characteristic strength values from samples with as few as 40 specimens. This requires the application of a penalty factor, but currently used factors are too high and should be lowered to 0.5 for small samples of 40 pieces and 0.8 for samples with 100 pieces.

The calculation method for characteristic values is also of interest when settings for grading machines are derived. In grading, it is usually the strength that determines the settings not MOE or density. In the process, the assumed distribution directly influences the yield within a strength grade. If large datasets are available, log-normal distributions result in the highest declared bending strength values and therefor the yields are also high. However, this is not true for tension strength classes as within single grades the coefficients of variation are high compared to C-classes (bending). Differences between the assumed distributions tend to increase with decreasing sample size. In addition to strength, density may also be a decisive factor for spruce assignments. Any of the applied parametric calculation methods leads to wrong estimations of the actual distribution as modern grading techniques usually allow exact property prediction and therefor lead to truncated distributions.
Independent of the applied calculation method, settings are strongly influenced by local variations in timber properties. This factor becomes more important when large grading areas need to be assessed. Countries should not be combined to grading areas without checking conformity. An easy to use method for conformity analysis is proposed. The cross-check with the currently used grading procedure shows that this method can be used to identify countries that can be combined into a single grading area.

Comparing the two grading methods – visual and machine – it is obvious that there is a clear effect on the strength, stiffness and density values of the timber samples of equal strength classes. Due to the current method used for the derivation of settings for grading machines, it cannot be guaranteed that machine graded timber shows a better performance than visual grading. However, this is only happening in a limited number of cases. Calculated safety factors show that machine strength grading is able to decrease the cov of the material to an acceptable level, at least for higher strength classes or strength class combinations. This contradicts the advantages provided for visual grading today. Based on limited test data visual grading methods are applied on a larger area, on more cross-sections and a variety of species. As the principles of the two methods are similar, efforts need to be undertaken to treat visual and machine grading equally.

5 Summary of Publications

5.1 Efficiency of visual strength grading of timber with respect to origin, species, cross section, and grading rules: a critical evaluation of the common standards

Strength grading is essential for the efficient use of structural timber. While international standards exist for machine strength grading, visual grading is still regulated based on national rules, which are expected to allow safe and economic grading results. However, there are large differences in the graded output because species, cross-section, and origin of the timber influence the results, though some of these standards are considered to be applicable universally. The present paper demonstrates how the chosen standards influence the grading results. Depending on the parameters, the yields or the mechanical properties are low compared to the declared values. The results also show the efficiency and applicability of different national standards for strength grading of timber from various origins. Furthermore, it is recommended to reconsider the existing limits for source areas and cross-sections given in the standard EN 1912.

The author conducted a large part of the laboratory work, in cooperation with technical staff and student assistants and did all of the calculations and analysis. Programming the grading for INSTA and NF rules was done by Andreas Gossler during his Master's thesis under supervision of Olaf Strehl and the author. The co-author contributed to content and language of the manuscript.

5.2 Influence of cross-section and knot assessment on the strength of visually graded European Norway spruce

The strength of graded timber is determined by a multitude of parameters. Properties of interest are the shape of the cross-section and the wood quality. With regard to strength, wood quality is primarily expressed in terms of knots and knot clusters which, together with the cross-section of the timber, are used to calculate knot ratios. By applying the visual grading rules as given in the German standard DIN 4074-1, the influence of different timber sizes on grading results has been analysed. Different grading approaches for joists and boards exist and are taken into account in the assessment of 5665 specimens originating from various parts of Europe. It was shown that both the cross-section and the grading method have a major influence on the characteristic strength values of Norway spruce. Limitations of the current standard with respect to its applicability to certain cross-sections are exposed. Alternative, simple grading approaches for boards are proposed. They ensure equal strength values and comparable yields as compared to the rather complicated board rules used nowadays.

The author conducted a large part of the laboratory work, in cooperation with technical staff and student assistants and did all of the calculations and analysis. The co-author contributed to content and language of the manuscript.

5.3 Influence of sample size on assigned characteristic strength values

According to EN 384, characteristic values for strength need to be adjusted for sample size and number of samples. The minimum sample number is 1 and the minimum sample size allowed is 40. With decreasing number of samples the statistical punishment factor (ks-factor) reaches a minimum value of 0.78. It means that for a single grade and species, 40 specimens may be sufficient in order to determine characteristic strength values to be used with Eurocode 5. This minimum of 40 specimens is independent of the size of the growth area, generally considered as being one country. Since the introduction of EN 384, a large number of wood species and grades have been assigned to strength classes, varying from softwoods (mainly spruce and pine), low and medium dense European hardwoods like poplar, ash and maple to heavy tropical hardwoods such as cumaru und massaranduba. In this paper, a statistical analysis has been made for a number of species for which data is available. The influence of the sample size on the derived characteristic values is studied together with an analysis of the variation in (characteristic) strength values between subsamples. It is shown that EN 384 can be too liberal. The derived characteristic strength values of species, subsamples and grades are studied using the ranking method and 2-parameter weibull distributions. A proposal for an improvement in the current procedure to determine characteristic strength values on the basis of small samples is made.

Peer review of papers for the CIB-W18 Proceedings

Experts involved:
Members of the CIB-W18 “Timber Structures” group are a community of experts in the field of timber engineering.

Procedure of peer review

- Submission of manuscripts: all members of the CIB-W18 group attending the meeting receive the manuscripts of the papers at least four weeks before the meeting. Everyone is invited to read and review the manuscripts especially in their respective fields of competence and interest.
- Presentation of the paper during the meeting by the author
- Comments and recommendations of the experts, discussion of the paper
- Comments, discussion and recommendations of the experts are documented in the minutes of the meeting and are printed on the front page of each paper.
- Final acceptance of the paper for the proceedings with
    - no changes
    - minor changes
    - major changes
    - or reject

Revised papers are to be sent to the editor of the proceedings and the chairman of the CIBW18 group

Editor and chairman check, whether the requested changes have been carried out.

The author conducted a large part of the laboratory work, in cooperation with technical staff and student assistants and did most of the calculations and analysis. The third co-author provided data and performed calculations for tropical hardwoods. The second co-author contributed to content and language of the manuscript.

5.4 Analysis of determination methods for characteristic timber properties as related to growth area and grade yield

The origin of the raw material is a key aspect for strength grading of timber. Large grading areas are favoured by the sawmilling industry as they require less effort in handling and documentation during the production process. However, large growth areas can also cause problems, as too high mechanical properties can be declared or yields may become uneconomical.
The presented study presents a method that should allow for timber from different countries to be combined into a single grading area. Additionally, the influence on the yield for guaranteeing timber properties for differently defined populations is analysed. In this process, a number of available calculation methods for characteristic values for MOR, MOE and density are considered as the determination method also influences the final yield. Non-destructive and destructive test data from 8487 spruce specimens from Europe tested in bending or tension is the basis for the presented study.
Based on the grading results the presented method is able to simply identify countries that may be combined. The definition of pan-European grading areas seems problematic if characteristic timber properties need to be guaranteed separately for each individual country as it may result in a severe drop in yield. However, checking timber properties only for the European population is unsatisfying as calculated timber properties considerably vary depending on the origin. As for the calculation method, the preferred method itself seems to have less impact on bending class assignments then on tension class assignments.

The author conducted a large part of the laboratory work, in cooperation with technical staff and student assistants and did all of the calculations and analysis. Both co-authors contributed to content and language of the manuscript.

5.5 Effects of grading procedures on the scatter of characteristic values of European grown sawn timber

The natural scatter in mechanical properties of sawn timber must be reduced by grading the material either visually or mechanically. Depending on the grading procedure, the scatter of these properties varies. This study deals with their variation as influenced by the grading procedure.
The effect of the grading principle is analyzed based on 4893 sawn timber specimens from several European natural forests with widths up to 167 mm and depths up to284 mm and using the method given in EN 14081-2:2010. Grading models for visual grading and machine grading are derived considering different source countries, strength classes and strength class combinations. Material safety factors for the graded material are then estimated in accordance with ISO 2394 to evaluate the grading outcomes.
Analyzing and comparing the lower 5th-percentile to the requirements of EN 384, it is found that the actual strength for class C24 can be up to 20% lower than required by the standard. This is true, regardless of whether the timber is graded visually or by an advanced grading machine using dynamic modulus of elasticity and knots. Low strength values can be expected especially in cases where a batch of timber is graded into a single strength class and reject only. High coefficients of variation of the graded material lead to the conclusion that high material safety factors are needed. On the contrary, if the material is graded by a machine and into more than two strength classes in one pass, it can be shown that the required material safety factors can be lower.

The author conducted a large part of the laboratory work, in cooperation with technical staff and student assistants and did most of the calculations and analysis. The co-author contributed to calculations and to content and language of the manuscript.

5.6 Other publications

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I

Efficiency of visual strength grading of timber with respect to origin, species, cross section, and grading rules: a critical evaluation of the common standards.

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Abstract

Strength grading is essential for the efficient use of structural timber. While international standards exist for machine strength grading, visual grading is still regulated based on national rules, which are expected to allow safe and economic grading results. However, there are large differences in the graded output because species, cross-section, and origin of the timber influence the results, though some of these standards are considered to be applicable universally. The present paper demonstrates how the chosen standards influence the grading results. Depending on the parameters, the yields or the mechanical properties are low compared to the declared values. The results also show the efficiency and applicability of different national standards for strength grading of timber from various origins. Furthermore, it is recommended to reconsider the existing limits for source areas and cross-sections given in the standard EN 1912.

Keywords: grading standard; mechanical properties; sawn timber; timber grading; timber source

Introduction

The major part of structural timber on the European market is graded visually. While for machine graded timber European standards are commonly used (EN 14081-2 & EN 14081-3), visual grading is done mainly based on national standards. These national standards are supposed to optimise the grading results for the timber resources of the country, taking into account growth conditions, local preferences for certain cross-sections, silvicultural differences, and historical developments concerning structural applications. National grading rules are assessing differently the knot size, growth ring width, or (local) slope of grain. Depending on the standard, the raw material can be graded into up to four grades, for instance according to the Scandinavian standard INSTA 142.

To facilitate the exchange structural timber between different markets, European standard EN 1912 lists how national grades are related to strength classes as given in EN 338. Assignments are restricted not only for certain species, but also for geographical areas or certain cross-sections for which the national grading rules are valid. For additional entries in EN 1912, scientific reports or a proven record of long experience are required concerning a certain wood species in its application. It is required that the test material is representative for the whole population with regard to timber source, sizes, and qualities. To cover these aspects, physical testing usually requires a considerable amount of test pieces. A large variation in physical properties is to be expected, as wood species generally grow over large geographical areas on different soils and under various climatic conditions.

The testing efforts of today are in contrast to the assignments which have been introduced 15 years ago, when the European market was created. For some grading standards, large growth areas were specified at the same time. An extreme example is spruce originating from the growth area Central, North and Eastern Europe (CNE Europe).

There are only a few publications focusing on the comparison of national grading rules. Johansson et al. (1992) compared INSTA, DIN and ECE rules. Spruce timber from Germany and Sweden was graded and tested in bending (255 pieces) and tension (245 pieces). When compared to published strength values for the highest grade of INSTA and DIN, the reached bending strength values were much higher than the declared values. INSTA T3 class reached a 5%-characteristic bending strength of 38.5 MPa, while DIN S13 class reached 36.9 MPa in bending as compared to 30 MPa declared for both grades. Also, all lower classes showed significant higher values than expectable from the current strength class assignments in EN 1912. Similar effects were found for modulus of elasticity (MoE) and density. However, the results were not analysed separately for the different origins. Small scale comparisons for a limited number of specimens were carried out by Almazán et al. (2008) for German pine graded by DIN 4074 and UNE 56544 or by Riberholt (2008) for European spruce graded according to Chinese visual rules. Visual grading is addressed in several available CIB-W18 Timber structures publications (Fewell 1984; Uzielli 1986; Barrett et al. 1992; Stapel et al. 2010), but none of these focused on the comparison of different grading rules and the assignment according to EN 1912.

Verification of the validity of grading standards for such large growth areas as CNE is the main goal of the present paper. Softwoods (spruce, pine, larch, Douglas fir and Sitka spruce) will be graded and tested in tension or by edgewise bending. The following grading standards will be in focus: DIN 4074-1:2012-06, BS 4978:2007+A1:2011, DS/INSTA 142:2009 (E), NF B 52-001-1:2011 and SIA 265/1:2009. Three main factors will be analysed with particular emphasis on: The available cross-sections, the applied grading standards, and the geographical source of the timber.

Materials and methods

Table 1: List of symbols and abbreviations.

Symbol	Definition
BS	British visual grading standard
CE	Central Europe
CH	Switzerland
CNE	Central, North and Eastern Europe
cov	Coefficient of variation
DEK	Important knot parameter used for DIN grading
DIN	German visual grading standard
DIN-B	Grading rules for boards given in DIN
DIN-K	Grading rules for joists given in DIN
E_0	Modulus of elasticity (MPa)
$E_{0,mean}$	Modulus of elasticity (MPa) - Mean value
EE	Eastern Europe
f_m	Bending strength (MPa)
$f_{m,k}$	Bending strength (MPa) - 5th percentile value
FI	Finland
FR	France
f_t	Tension strength (MPa)
$f_{t,k}$	Tension strength (MPa) - 5th percentile value
INSTA	Scandinavian visual grading standard
LV	Latvia
MoE	Modulus of elasticity
n	Number of specimens
NF	French visual grading standard
PL	Poland
RU	Russia
R^2	Coefficient of determination
ρ	Density [kg m^{-3}]
ρ_k	Density - 5th percentile value [kg m^{-3}]
SE	Sweden
SI	Slovenia
SIA	Swiss visual grading standard
SKA	Single knot data is available
tKAR	Total knot area ratio
UK	United Kingdom

Materials and data sets concerning the knot evaluation: Altogether, 12837 specimens were analysed. The dataset is divided for two loading modes (edgewise bending and tension) and for two knot descriptions. In 60% of all cases, every single knot of the specimen was measured. This is classified as single knots available (SKA, abbreviations are summarized in Table 1). These SKA data formed the basis for analysing the influence of the cross-section and the grading standard. For the remaining 40%, no single knot data was available but the (largest) knot area ratio (tKAR) could be measured. The influence of the geographical source of the timber was analysed based on the tKAR data. Table 2 summarizes the available data sets. The used material was sampled on sawmill level. No requirements for the log quality were defined but regional available logs were used. The boards of the logs are considered as sawfalling material, which is in line with the procedure used for the derivation of mechanical properties of sawn timber or the derivation of machine settings. All specimens with available SKA values were tested at the institute ‘Holzforschung München’ between 1995 and 2012. The remaining specimens were tested at various laboratories around Europe during the Gradewood project that finished in 2011 (Ranta-Maunus et al. 2011).

Table 2: Summary of the available data.

Data	Bending	Tension	Total
Number of specimens	5773	7064	12837
Only tKAR data available	2719	2477	5196
tKAR and SKA data available	3054	4587	7641

Destructive tests were performed according to EN 408:2010 for both bending (symmetrical two point loading, span: 18 times the depth) and tension (span: 9 times the depth). The orientation of the board in edgewise bending tests was chosen randomly. The modification factors for test set-up and specimens sizes given in EN 384:2010 have been applied (k_h-factor for depth, k_l-factor or length). Whenever possible, the weakest section along the beam axis was tested. The original beam length from which the specimens were cut was in most cases more than 4000 mm.

The most important visual grading parameters for the SKA data: knots, knot clusters and growth ring width. The knots’ position was determined with an accuracy of 1 mm. Knots smaller than 5 mm were not recorded. The knots were only analysed in the section between or close to the loading points, for the bending tests, while for the tension tests the knots were analysed between the grips. Visual grading for the analysis of geographical origin has been performed based on the total KAR (tKAR) value, as SKA data were not available for all specimens (Table 2). The tKAR is defined as the knot area within 150 mm projected on the end grain divided by the area of the cross section (BS 4978). Overlapping knot areas are counted only once. Table 3 summarizes the available data and gives mean values and coefficients of variation (cov) for strength, MoE, density, and tKAR. (CE=Central Europe, EE=Eastern Europe). Values for strength are always rounded to one decimal place, for values for density no decimal places are presented. The MoE data are rounded to the nearest hundred. While mean values and cov are presented for the ungraded dataset, these figures are not given for the grading results in order to keep the tables clear. However the variation within one grade is a quality feature of the material and is briefly addressed when appropriate.

It is necessary to differentiate between SKA and tKAR only datasets. For pieces with SKA data, more grading rules have been considered. For the tKAR dataset, thresholds have been defined for different grades based on the visual grading standards DIN 4074-1 and BS 4978. For these standards, many geographical sources are listed in EN 1912. 5^{th}-percentile values of the strength and density are determined non-parametric in accordance with EN 384; for modulus of elasticity (MoE), the mean is determined. Specimens tested in edgewise bending as well as in tension were considered for the analysis, although assignments in EN 1912 are based on bending strength only. Tension test results are compared to those given in EN 338, which in turn are based on the bending strength multiplied by the factor 0.6, which is expected to be on the safe side.

Table 3: Mean values and coefficient of variation (*cov*) for bending or tension strength ($f_{m/t}$), modulus of elasticity (E_0), density (ρ) and tKAR given for different testing modes, species and sources.

Load mode and species	Source	n Total	SKA	$f_{m/t}$ [MPa]	E_0 [MPa]	ρ [kg m^{-3}]	tKAR [-]
				Mean values and *cov*[a]			
Bending							
Pine	PL	219	0	39.0	12500	515	0.26
				0.42	*0.28*	*0.10*	*0.59*
	SE	209	0	45.1	11300	481	0.21
				0.34	*0.24*	*0.09*	*0.47*
Sitka	UK	607	607	29.6	7900	404	0.37
				0.31	*0.29*	*0.10*	*0.35*
Spruce	CE	1880	1880	39.1	11500	438	0.27
				0.33	*0.26*	*0.12*	*0.42*
	EE	840	0	35.7	10000	396	0.30
				0.31	*0.24*	*0.10*	*0.35*
	FR	115	0	42.8	11800	440	0.22
				0.26	*0.20*	*0.10*	*0.40*
	PL	433	432	38.5	11400	434	0.32
				0.31	*0.25*	*0.11*	*0.32*
	SE	345	135	42.5	11800	450	0.26
				0.36	*0.26*	*0.13*	*0.42*
	SI	1125	0	43.7	12000	445	0.25
				0.30	*0.24*	*0.10*	*0.40*
Tension							
Douglas	CE	324	324	24.8	10900	493	0.36
				0.50	*0.25*	*0.11*	*0.33*
Larch	CE	326	326	26.8	10400	540	0.31
				0.47	*0.27*	*0.11*	*0.39*
Pine	CE	264	264	25.3	10400	525	0.31
				0.42	*0.25*	*0.12*	*0.39*
	FI	257	0	31.7	11400	492	0.25
				0.39	*0.20*	*0.11*	*0.41*
	FR	239	0	20.3	9000	512	0.32
				0.41	*0.25*	*0.09*	*0.37*
	PL	456	455	28.6	11300	529	0.26
				0.44	*0.26*	*0.11*	*0.53*
	RU	171	0	20.4	9600	442	0.33
				0.43	*0.22*	*0.10*	*0.34*
	SE	206	0	29.7	10400	485	0.24
				0.39	*0.22*	*0.09*	*0.41*
Spruce	CE	2895	2895	30.4	11500	448	0.28
				0.40	*0.23*	*0.11*	*0.40*
	CH	442	0	25.1	10900	439	0.28
				0.45	*0.24*	*0.12*	*0.41*
	EE	844	0	26.2	10300	395	0.30
				0.42	*0.21*	*0.10*	*0.34*
	LV	106	106	30.4	11700	466	0.33
				0.38	*0.24*	*0.11*	*0.37*
	PL	219	217	28.5	11600	446	0.30
				0.37	*0.23*	*0.12*	*0.38*
	SE	211	0	27.4	10100	415	0.24
				0.38	*0.23*	*0.12*	*0.46*
	SI	104	0	34.0	12300	442	0.25
				0.44	*0.22*	*0.09*	*0.43*

[a] cov values are in italics.

The available SKA data are separated for thickness of pieces, to check the influence of the dimensions on the grading results for the DIN and BS standards. The thickness was favoured over the width or the cross-sectional area of the specimens as it has the strongest influence on the grading of joists according to DIN rules. The frequency of the thickness is shown in Figure 1 for pieces tested in bending and in tension. In a first step, six different categories were formed with an equal number of pieces in each group. This was done for spruce independently of the loading mode. In a second step, the results for spruce tested by bending were analysed more precisely, forming four different thickness groups: ≤37 mm, 38 - 45 mm, 46 - 60 mm, > 61 mm. The boundaries were chosen to cover the important size of 38 - 45 mm for timber frame and 46 - 60 mm, and > 61 mm for typical roof structures in CE. For these pieces, the resulting strength in the different classes was analysed additionally.

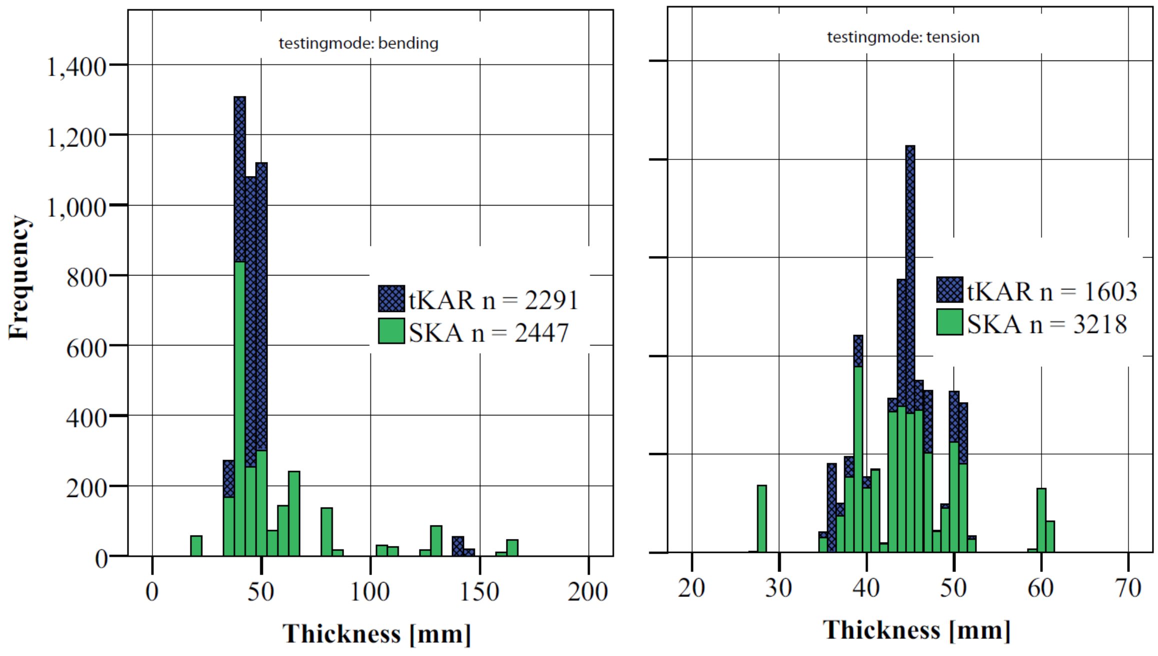

Figure 1: Frequency distribution for thickness divided by bending and tension, showing the available knot data.

The following grading standards have been applied based on SKA data: DIN 4074-1, BS 4978, INSTA 142, NF B 52-001-1 and SIA 265. DIN 4074-1 includes different sets of grading rules for the German designations “Kantholz” (joists), “Brett/ Bohle” (boards) and “Latten” (battens). The joist-grading is used for all pieces loaded in edgewise bending. Both grading rules for joists and boards have been applied, depending on the sizes and cross section shape (DIN 4074-1). Unless the boards are for glulam production, edge knots have to be considered in a special way. This optional criterion, called in German “Schmalseitenast”, has been applied as well.

Differences between grading rules are partly due to the parameters of knot measurements, which can be done by determination of the minimum knot diameter, the knot projected on the end grain of the board or the knot size measured parallel to the edge of the board. Not only single knots, but also knot clusters are considered in all of the standards. The length of the board over which the single knots are added up to a knot cluster is for some standards equal to the width of the board, other standards consider a common length of 150 mm. Additional parameters are: growth ring width, compression wood, and the appearance of a pith, when such parameters are specified as grade determining features in the respective standards. Some of these parameters have to be taken into account only for certain species or sizes.

The SIA rules allow for different measuring principles for grading of boards or joists. Our analysis is limited to the grading of joists. The INSTA rules depend on the shape of the cross-section. Timber with thicknesses between 25 and 45 mm and a width between 50 and 75 mm has not been considered. This lowers the number of available pieces for the INSTA analysis, but 6921 pieces were still available. The French standard NF B 52-001 refers to EN 1310 for the measurement of features. The NF itself considers different thresholds depending on the species. Only spruce and pine will be analysed. For both standards, the definitions of knot types are not unambiguous and leave some room for interpretation. The standards were discussed with grading experts from the respective countries and applied to the best of our knowledge.

The differences between grading standards are not only caused by different ways of determining knot sizes, but also because the number of classes vary. Where BS has two classes, INSTA and NF have four, not counting the reject. This fact influences the assignment of visual grades to strength classes in EN 338 as given in EN 1912.

The strength classes that correspond to the visual grades for the main softwood species spruce, fir, and pine are listed in Table 4. For a better overview, minor differences for single species are not differentiated in this table. The SIA classes are not included in EN 1912, but corresponding strength classes are given directly in the SIA. The grade allocation given in

Table 4 is only valid for a specified source area. DIN and BS are valid for timber from CNE, INSTA for Northern and North Eastern Europe and NF for France only. SIA does not specify a certain area for which its grading rules can be applied.

Table 4: Strength class requirements for characteristic values of bending strength ($f_{m,k}$), modulus of elasticity ($E_{0,mean}$) and density (ρ_k) according to EN 338 and corresponding visual grades as given in EN 1912 for main softwood species.

EN 338	$f_{m,k}$ [MPa]	$E_{0,mean}$ [MPa]	ρ_k [kg m^{-3}]	DIN	BS	INSTA	NF	SIA
C 35	35.0	13000	400	-	-	-	-	-
C 30	30.0	12000	380	S13	-	T3	ST1	-
C 27	27.0	11500	370	-	-	-	-	-
C 24	24.0	11000	350	S10	SS	T2	ST2	FKI&FKII
C 20	20.0	9500	330	-	-	-	-	FKIII
C 18	18.0	9000	320	S7	-	T1	ST3	-
C 16	16.0	8000	310	-	GS	-	-	-
C 14	14.0	7000	290	-	-	T0	ST4	-

In the first instance, C-classes were mainly in focus. Later on, the actual strength class assignments are given for all grades, species, and loading modes according to EN 1912 or national standards. For some species or loading modes, there are no assignments. In this case, the assignments are linked to the grades given in Table 4.

More data are available if only tKAR values are used. These require the derivation of fixed threshold values (tKAR), as – other than for national grading rules – there are no grades based on tKAR only. The thresholds are derived for DIN and BS. The yield was matched for both grading options based on the SKA data set. As an example: SKA and tKAR data are available for 2447 pieces graded according to DIN (joists). For the DIN grading into S13 a maximum knot value of 0.2 is allowed. In addition, other parameters also need to be considered during grading. If DIN grading results in a yield of 18%, an appropriate KAR value is chosen leading approximately to the same yield.

The grading results from the tKAR dataset are analysed with special respect to the geographical source of the timber, as specimens from many regions were available with tKAR values. The cross-section itself, though it may be relevant, is not considered during this step. This seems acceptable as both DIN and BS do not have restrictions for the cross-sections. For this part of the analysis, the focus is on spruce and pine tested in bending. For timber loaded in tension single aspects are highlighted.

Results and discussion

Cross-section analysis

Figure 2 shows the influence of the thickness for the most important grading parameters of DIN (DEK-value) and BS (tKAR-value). Based on the increasing R^2-values, it is obvious that with higher thicknesses the results from knot measurement rules slowly converge, even though the correlation remains low. This means that single pieces graded according to BS and DIN will be more likely assigned to the same strength class for high thicknesses rather than for small thicknesses. At higher thicknesses, very large knot values are not detectable by any of the standards.

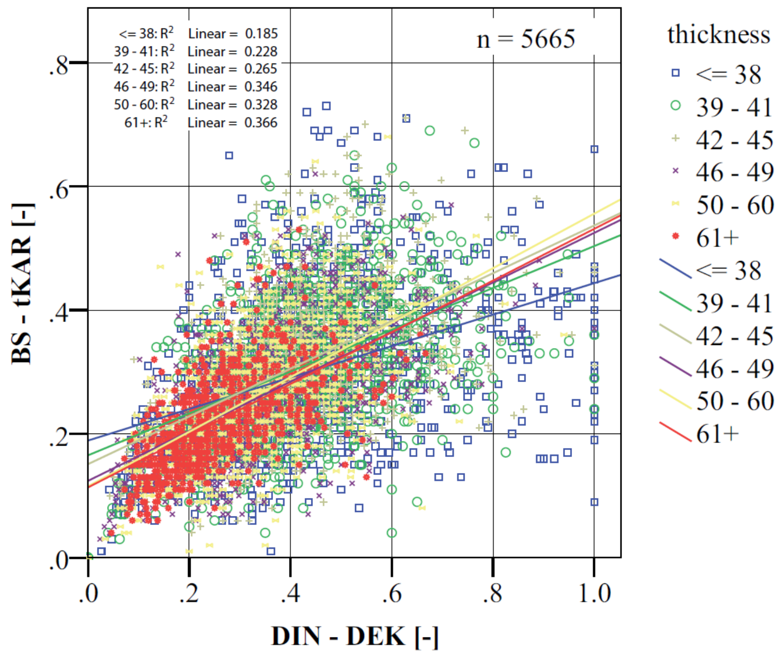

Figure 2: Important grading parameters tKAR (BS) and DEK (DIN) influenced by the thickness.

The influence of the cross-sections on the strength were tested, and in Figure 3 the thicknesses are grouped again and are plotted against the strength focusing on the main DIN and BS grading parameter. The quality of the strength prediction is higher for the BS. Both DEK and tKAR promise higher strength prediction accuracy for small thicknesses. The grade determining properties are not only based on the knot values presented in Figure 3. The results obtained under consideration of other grade determining properties are presented in Table 5. All MoE and density values in Table 5 meet the requirements. The strength values are slightly below or above the required strength values for thickness-classes of 38-45 mm and 46-60 mm. The worst case within these two groups results from 384 pieces graded into C24. The characteristic strength reaches a value of 21.9 MPa or 10% below the required value. Strength values for the largest and smallest thickness-class are too low for several grades. The class 60+ shows the lowest values for *cov* (coefficient of variation) of the bending strength in strength classes C30 and C24, independently of the standard.

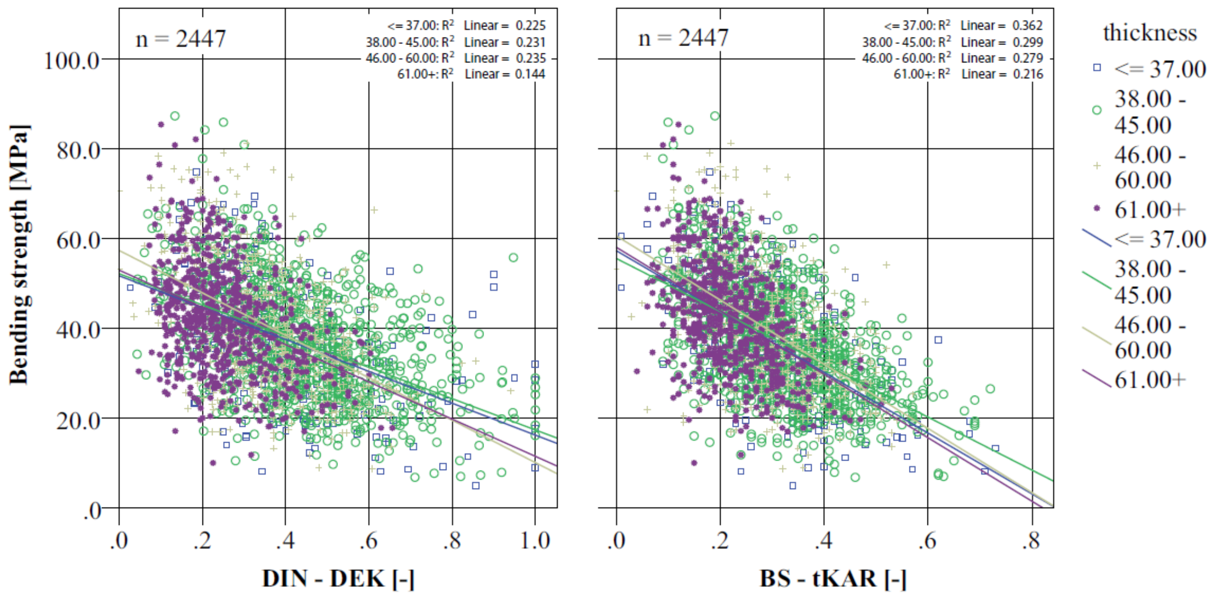

Figure 3: Scatter of knot values and quality of strength prediction for DIN and tKAR separated for thickness – for spruce tested in bending.

Table 5: Grading results for different cross-sections – for spruce tested in bending.

Thickness [mm]	Strength class	Grading rule	n	$f_{m,k}$ [MPa]	$E_{0,mean}$ [MPa]	ρ_k [kg m^{-3}]
<= 37	C30	DIN	28	26.3	15200	387
	C24	BS	111	28.4	14300	387
	C24	DIN	94	17.1	13200	364
	C18	DIN	65	17.0	10700	347
	C16	BS	49	14.7	11100	350
38 – 45	C30	DIN	42	31.4	14300	403
	C24	BS	454	24.7	12600	371
	C24	DIN	384	21.9	12100	366
	C18	DIN	386	19.2	10700	368
	C16	BS	232	19.5	11000	372
46 – 60	C30	DIN	53	35.9	14900	398
	C24	BS	341	24.6	12900	357
	C24	DIN	310	23.1	12200	357
	C18	DIN	178	19.4	10500	354
	C16	BS	120	18.9	10500	352
61+	C30	DIN	164	26.9	12100	382
	C24	BS	597	26.1	12000	377
	C24	DIN	437	24.5	11800	366
	C18	DIN	68	21.3	10700	356
	C16	BS	56	18.2	9700	338

This is in-line with a lower variation of the ungraded material. However, the low variation of the graded material does not guarantee high characteristic strength values as for the 60+ class a total of 164 pieces is graded into C30 reaching a characteristic bending strength of just 26.9 MPa. Grading results for large and small thicknesses often do not fulfill the requirements. For large thicknesses, this is related to the knots, usually not reaching values of above 0.5 (DEK and tKAR) as can be seen in Figure 3. Downgrading of boards into C24 mainly based on relative knot sizes is apparently not accurate enough. However, for BS the strength values for C24 are high compared to the 38-45 mm and 46-60 mm thickness classes, as the larger cross-sections seem to lead to a homogenization of the material. Trying to assign higher classes than C24 according to BS rules would also cause problems as then the current grade may not fulfill the C24 requirements anymore. Considering absolute knot sizes like in EN 1310 could help to obtain higher strength values for larger timber dimensions. Actually, the NF which is based on EN 1310, reaches the required values for larger thicknesses, but unfortunately, in this case the yields are very low. For strength classes above C24, the size of the specimens should be a limitation for all used standards. Disregarding the cross-section for the allocation of national grades to C-classes is not justified.

Grading standard

The influence of different grading standards was analyzed by means of SKA. There are bending data available for spruce and Sitka spruce and tension test data for spruce, pine, Douglas fir and larch. In Table 6 the grading results are sorted by grading rules. In the following the single grading rules are pointed out.

Table 6: Grading results for different grading rules.

Rule	Load mode	Species	Strength class	n	$f_{m/t,k}$ [MPa]	$E_{0,mean}$ [MPa]	ρ_k [kg m^{-3}]	Yield [%]
BS	Bending	Spruce	C24	1503	25.6	12600	373	61
			C16	457	18.9	10700	361	19
		Sitka	C18	179	22.4	9400	347	30
			C14	178	17.5	7900	340	29
	Tension	Spruce	C24	1848	18.5	12500	376	57
			C16	662	13.8	10700	365	21
		Pine	C24	397	16.9	12300	453	55
			C18	155	10.2	9800	422	22
		Douglas	C18	92	16.3	12700	434	28
			C14	68	11.0	11100	425	21
		Larch	C24	147	15.6	11500	451	45
			C16	68	11.8	10500	439	21
DIN-B	Bending	Spruce	C30	297	28.2	14200	395	12
			C24	1012	20.7	11900	364	41
			C18	986	20.0	11000	363	40
		Sitka	C30	18	27.1	10900	361	3
			C24	160	21.4	9200	355	26
			C16	188	16.6	8300	350	31
	Tension	Spruce	C30	484	22.6	13600	393	15
			C24	1326	15.4	11700	368	41
			C18	1152	13.6	10900	368	36
		Pine	C30	113	28.2	14100	503	16
			C24	271	13.8	11200	434	38
			C18	252	11.0	10200	435	35
		Douglas	C35	43	17.7	13700	444	13
			C24	151	11.7	11000	427	47
			C16	113	8.5	10000	419	35
		Larch	C30	42	22.7	12400	478	13
			C24	145	12.3	10800	457	45
			C16	123	8.0	9500	449	38
DIN-K	Bending	Spruce	C30	287	28.7	13200	387	12
			C24	1225	22.8	12100	363	50
			C18	697	19.1	10700	361	28
		Sitka	C30	6	37.3	11100	392	1
			C24	219	20.0	8800	349	36
			C16	169	17.8	8400	354	28
	Tension	Spruce	C30	267	21.9	14000	397	8
			C24	1541	17.2	12000	369	48
			C18	1082	13.4	10700	369	34
		Pine	C30	91	26.6	13900	483	13
			C24	303	14.9	11800	448	42
			C18	225	10.4	9600	417	31
		Douglas	C35	27	17.8	13300	441	8
			C24	69	14.1	12100	434	21
			C16	117	12.9	10700	424	36
		Larch	C30	22	17.4	13300	485	7
			C24	138	13.8	11100	451	42
			C16	87	8.2	9800	446	27
INSTA	Bending	Spruce	C30	396	28.5	13500	389	18
			C24	619	25.6	12500	366	27
			C18	928	20.0	10900	359	41
			C14	210	12.8	9700	360	9
		Sitka	C24	52	16.1	8500	351	9
			C24	127	19.7	8900	345	21
			C18	239	15.1	7900	337	39
			C14	95	15.3	6800	345	16
	Tension	Spruce	C30	371	21.8	13600	382	13
			C24	760	19.2	12400	369	27
			C18	1197	15.1	11100	366	43
			C14	327	11.3	9900	365	12

Rule	Load mode	Species	Strength class	n	$f_{m/t,k}$ [MPa]	$E_{0,mean}$ [MPa]	ρ_k [kg m^{-3}]	Yield [%]
INSTA	Tension	Pine	C30	98	25.7	13800	499	16
			C24	129	18.2	12400	450	22
			C18	231	11.9	10500	415	39
			C14	89	8.8	9200	429	15
		Douglas	C30	17	17.6	13900	467	5
			C24	35	10.6	13000	435	11
			C18	132	13.4	11000	426	41
			C14	88	9.5	9900	416	27
		Larch	C30	36	16.8	12700	471	11
			C24	62	16.6	11600	452	19
			C18	126	8.6	9900	442	39
			C14	59	11.9	9700	461	18
NF	Bending	Spruce	C30	52	28.1	14300	373	2
			C24	763	20.5	12400	371	31
			C18	897	21.1	11500	359	37
	Tension	Spruce	C30	178	24.4	14000	406	6
			C24	1167	17.0	12000	371	36
			C18	1065	14.7	11300	364	33
		Pine	C30	16	12.0	13200	499	2
			C24	158	20.0	13100	471	22
			C18	200	12.7	10800	434	28
			C14	257	10.2	10100	431	36
SIA	Bending	Spruce	C24	100	30.5	14300	409	4
			C24	369	23.8	12800	377	15
			C20	390	22.8	12100	366	16
		Sitka	C24	5	39.1	10700	409	1
			C24	39	22.1	9400	331	6
			C20	62	17.9	9000	332	10
	Tension	Spruce	C24	180	23.1	14300	412	6
			C24	272	17.7	12800	371	9
			C20	379	18.0	12300	372	12
		Pine	C24	67	25.5	14000	487	9
			C24	62	19.4	12600	480	9
			C20	91	14.5	11500	450	13
		Larch	C24	14	27.4	13700	498	4
			C24	40	15.8	12000	472	12
			C20	39	8.0	10600	431	12
		Douglas	C24	15	17.6	15000	465	5
			C24	34	16.0	12900	436	11
			C20	18	11.5	11700	441	6

BS: Grading according to BS results in characteristic values above the requirements for all species, loading modes and grades. Therefore, the assignments can be considered as safe. The main reason for this is that C24 is the highest possible grade. If the rules are applied correctly, reject rates are high. They vary between 20% for spruce up to 51% for Douglas fir. Due to the sophisticated and rather complicated measuring method it is questionable, if these high reject rates are actually reached in practice.

DIN-B: As no assignment is given in EN 1912 for grading according to the DIN rules for boards, visual classes listed are based on the rules for joists. The results are above the requirements for spruce and pine tested in tension. For other possible combinations of species and load mode, the strength requirements are not fulfilled in several cases. The suggested strength classes for Sitka spruce are too high. Grading spruce joists according to board rules leads to the following results: The target value for C24 is clearly missed as only 20.7 MPa is reached. For spruce C30, a characteristic strength of 28.2 MPa is reached, for C18 20.0 MPa. However, with 20.7 MPa the strength for C24 is too low.

DIN-K: Strength values for Sitka spruce, larch and Douglas fir do not meet the requirements for the listed strength classes. Also for spruce tested in bending, the strength requirements are shortly missed. The results of tension tests for spruce and pine are safe.

Looking more closely at the grading of Sitka spruce, strength classes used in the BS would give satisfactory results. For DIN-K this would mean assigning S10 and higher to strength class C18. For Sitka spruce, one should focus on MoE as this is usually the grade restricting property. Having 225 pieces in one grade would result in a MoE value of 8900 MPa. The yields resulting from DIN are higher compared to yields from BS. This is not only true for Sitka spruce, where the reject is lower by 5%, but also for spruce tested in bending, where reject is only half of that of BS. The yields for C24 and higher are comparable.

INSTA: For spruce and pine, the reached strength values are above or close to the requirements. Generally speaking, the INSTA seems to work well for pine and spruce from Central Europe. Douglas and larch show strength values below the requirements in single classes. For Sitka spruce most strength requirements are not fulfilled. Depending on the combination of loading mode and species, the reject rates vary between 5 and 16%. Application of the additional strength class of C14 leads to a lower total reject rate. No other standard gives less reject. However this does not mean that the yields in higher classes are especially high. Unlike the BS, the INSTA assigns Sitka spruce to the strength classes C24, C18 and C14. As the source given in EN 1912 for the INSTA is not the UK, but Norway and

Denmark, the possible higher quality of Sitka spruce from these countries could be the reason for these different results. Classes above C20 can definitely not be reached for Sitka spruce from the UK.

NF: Required characteristic values are achieved except for the strength values of C30 and C24 for spruce tested in bending and for C30 of pine (n=16 only). The yield in C30 is low, while yields in C24 and C18 are comparable. Application of absolute knot values as grading criterion is unique among the analyzed standards. This is also an important reason why the yields in C30 are low compared to the other standards. The effectiveness of this method cannot be demonstrated by the resulting characteristic values. The bending strength for C24 is 20.5 MPa, while 21.1 MPa is obtained for C18. Hence this standard does not seem applicable for grading Central European spruce or pine.

SIA: For SIA no strength classes higher than C24 are listed in the national standard. The two national classes FK1 and FK2 are both assigned to strength class C24. Characteristic values are usually kept, while reject values are extremely high. Knots in the SIA are measured at right angles to the length of the pieces, which is comparable to most other grading standards, but very restrictive threshold values lead to high reject rates. A value of 1:3 for the ratio of the single knot compared to the width results in rejection of a piece. According to the INSTA rules, single knots of that size are still allowed for the grade C30. The practical use of the SIA standard with reject rates between 65% and 83% does not seem possible.

Comparing the *cov* values for species, the lowest *cov* of in-grade timber can be found for spruce tested in bending independently of the used standard. DIN and BS show similar results across all strength classes (*cov* 0.27 – 0.30) but INSTA rules lead to lower *cov* values. NF shows the highest *cov* values except for the highest strength class C30 (*cov* 0.24). Independently of the standard, none of the grades shows a *cov* less than 0.24. Highest *cov* values are found for Douglas fir.

Source

The influence of the geographical source threshold values was analysed only by tKAR. These data are determined in such a way that approximately the same yield is obtained as in DIN or BS. For the DIN grading, the single knot value DEK is plotted against the tKAR (Figure 4). This means for DIN that those pieces with tKAR values equal or below 0.16 are assigned to strength class C30. Of course, the pieces in this grade differ from those assigned to C30 (S13) by the exact DIN grading. For the BS, the difference is smaller because the main grading parameter is the tKAR value. However, BS also specifies a margin KAR value as a second important grading parameter. This value is based on knot measurements close to the edges of the pieces. In order to achieve the comparable yield, a number of margin KAR specimens are exchanged with tKAR specimens. Figure 4 makes the difference between DIN and BS rules obvious.

The consideration of the highest visual grades in both cases leads to the following results: For DIN, the new C30 grade (tKAR grading) consists of pieces originally graded into all possible DIN grades (SKA grading). S13 accounts for a maximum of 50% in the tKAR C30 grade. The BS pieces which are now assigned to C24 originate mainly from the SS grade. Only a small number of pieces originally graded into GS grade are added, where a margin KAR above 0.5 is combined with a total KAR between 0.2 and 0.29.

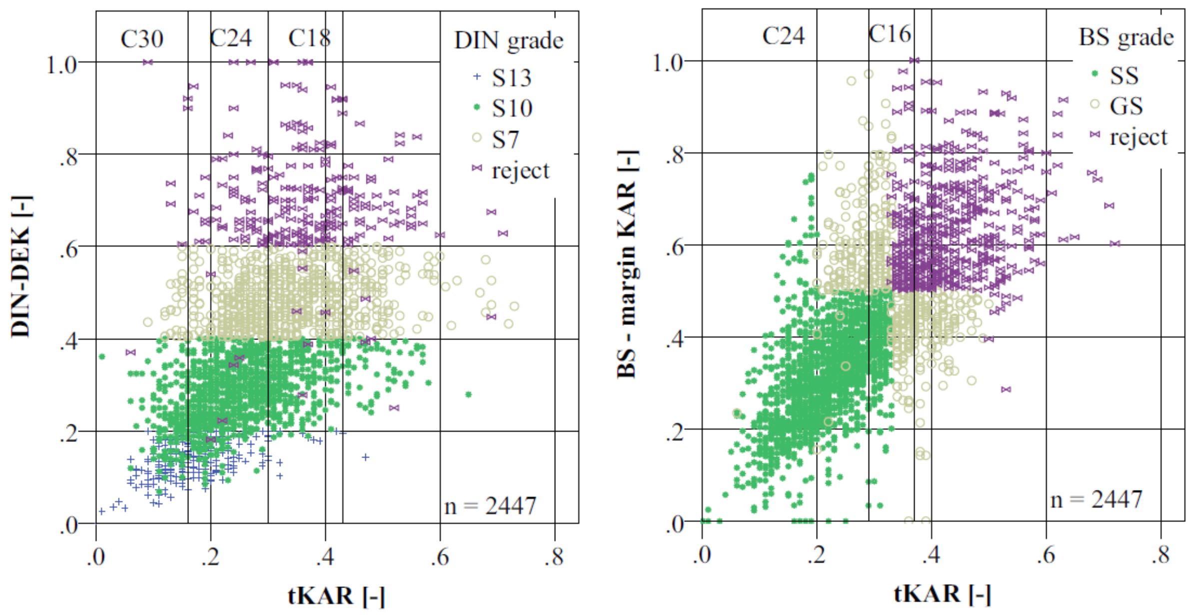

Figure 4: Illustration of the derivation of threshold values that are used for the grading of different sources for spruce tested in edgewise bending.

Table 7: tKAR values which give a comparable yield to the grading standards DIN or BS respectively.

	Spruce bending		Spruce tension		Pine tension	
	DIN	BS	DIN	BS	DIN	BS
C30	0.16	-	0.14	-	0.13	-
C24	0.30	0.29	0.29	0.29	0.29	0.29
C18	0.43	-	0.42	-	0.41	-
C16	-	0.36	-	0.36	-	0.37

The determined tKAR threshold values are given in Table 7. The influence of the testing mode or the species is small. For C24, the total KAR value is always 0.29 except for DIN grading, where this value is slightly higher (0.30). The differences reach a maximum for grading into C30 according to DIN yields. Values vary between 0.13 and 0.16 in this case. As these values are close together, the following grading procedure is based only on the total KAR values for spruce tested in bending and the results are considered representative for grading according to the standard.

Table 8: Grading results for different sources (bending only).

Source	Species	Strength class	Visual standard	n	$f_{m,k}$ [MPa]	$E_{0,mean}$ [MPa]	ρ_k [kg m^{-3}]	Yield [%]
CE	Spruce	C30	DIN	315	28.0	13400	390	17
		C24	BS	1186	24.8	12500	374	63
		C24	DIN	931	23.8	12100	367	50
		C18	DIN	471	17.2	10300	358	25
		C16	BS	337	18.9	10700	359	18
EE	Spruce	C30	DIN	73	28.5	11500	336	9
		C24	BS	424	23.6	11000	340	51
		C24	DIN	384	23.2	10800	342	46
		C18	DIN	289	18.0	9200	336	34
		C16	BS	200	20.0	9600	336	24
FR	Spruce	C30	DIN	31	25.1	12200	379	27
		C24	BS	94	26.5	12000	381	82
		C24	DIN	68	25.4	11800	375	59
		C18	DIN	14	16.5	11200	376	12
		C16	BS	15	23.3	11300	375	13
PL	Pine	C30	DIN	69	19.9	14400	452	32
		C24	BS	134	21.2	13900	441	61
		C24	DIN	70	21.5	13200	434	32
		C18	DIN	49	13.1	11000	435	22
		C16	BS	39	13.4	11200	434	18
	Spruce	C30	DIN	25	19.1	14600	411	6
		C24	BS	194	24.7	12800	373	45
		C24	DIN	188	24.4	12500	372	43
		C18	DIN	169	19.9	10500	356	39
		C16	BS	106	19.9	11100	356	25
SE	Pine	C30	DIN	73	30.1	13000	439	35
		C24	BS	165	26.5	11700	420	79
		C24	DIN	99	24.9	10700	412	47
		C18	DIN	34	15.3	9500	403	16
		C16	BS	31	15.1	9800	407	15
	Spruce	C30	DIN	63	24.5	12700	370	18
		C24	BS	231	23.7	12200	360	67
		C24	DIN	177	23.2	12000	355	51
		C18	DIN	74	15.2	11400	346	21
		C16	BS	58	13.8	11800	345	17
SI	Spruce	C30	DIN	231	34.8	13800	388	21
		C24	BS	798	27.4	12600	383	71
		C24	DIN	602	25.2	12000	379	54
		C18	DIN	246	20.4	10600	363	22
		C16	BS	194	21.1	10800	367	17

Table 8 contains the grading results for bending. As visible at the top of Table 8, the characteristic values for data from CE are lower, compared to the SKA grading, which includes timber from Poland and Sweden (Table 6). The calculated total tKAR value of 0.16 for C30 leads to a characteristic bending strength of 28.0 MPa instead of 29.1 MPa. This is acceptable as only tKAR was used and the results are based on the equivalence of yield in the different grades. However, these grading results have to be judged carefully, especially for the

DIN based results. The relative yield in the larger dataset is slightly higher, if only tKAR is used for grading. Throughout all grades, the characteristic values for BS are closer to the required values. This might be due to the fact that there is no grade for grading timber into C30 and therefore the better material is not graded into C30 but to C24 instead. On the contrary, one might also argue that in case of a higher grade, the grade boundaries for C24 (SS-Grade) would need some adjustment.

Eastern Europe

Independently of the grading procedure, the obtained strength values are close to the required ones. A considerable reduction in yield compared to Central Europe can be observed due to the low quality of the ungraded material (Table 3). 45% of the pieces do not reach strength class C24 or higher for DIN grading, but the assignment seems to be correct. Also the variation of strength values within the strength classes is small. Only timber from SI shows *cov* values within that range (0.22 – 0.29). Density values are well below the requirements as for the tKAR grading, but no parameter is available for predicting the density (growth ring width). The requirement for C30 is 380 kg m^{-3}, and only 336 kg m^{-3} is achieved. Looking at the characteristic values independent of the grade, it is questionable whether the growth ring width is sufficient to predict density, which is good enough and reach the density requirements for C24 or higher.

France

The dataset from France is too small for reliable statements with regard to the applicability of either DIN or BS standard.

Poland

For all classes and grading standards, the strength values are too low. This cannot be explained by low strength values for the ungraded material, as the mean value is in the range of ungraded spruce data. Also, the variation within the strength classes reaches a maximum compared to other countries (*cov* 0.31 – 0.38). MoE and density values are met. Visual grading of pine from Poland does not work when applying DIN or BS standards.

For spruce, except for the bending strength for class C30, which is only based on the minimum value of 25 pieces, the characteristic values are met. This does not indicate a high quality raw material. The values required for C24 are met, both for DIN and BS.

Sweden

For Swedish pine, yields are at least as high as for pine from Poland, though the characteristic values are met. For spruce, the characteristic values are close to the requirements except for C30 where 63 pieces out of 345 in this grade have a characteristic strength value of only 24.5 MPa.

Slovenia

Timber from Slovenia shows extraordinary good strength values for the timber properties in the ungraded dataset (Table 3) and consequently good grading results with low reject rates could be obtained. Graded based on the threshold values of DIN, the reject rate is as low as 3%. If the ungraded spruce material shows values which are constantly moving in the upper range of possible strength, MoE, and density distributions, the choice of the grading standard should be done focussing on the yield only, as the grading results will always be safe.

Grading output for tension is presented without precise listing of the results in a table and only single aspects are highlighted in the following.

Tension data (all sources)

Pine tension data is available from Finland (FI), FR, Russia (RU), and SE. Table 3 shows that there are already considerable differences in strength properties for the ungraded timber sources. These differences are reflected in the grading results. For timber from FI and

SE, the required values are reached. While the yields are close together, Finnish timber shows tensile strength values far above the requirements (26.8 MPa for C30, n=54/ 17.9 MPa for C24-DIN, n=123).

Timber from FR and RU shows clearly lower values for the ungraded samples (see Table 3) compared to timber from FI and SE. The tKAR grading leads to similar yields for timber from RU and FR. However, there is a difference in terms of obtained characteristic strength values. Grading FR timber into C24-BS leads to a characteristic strength of 8.9 MPa (n = 105), where 14.4 MPa is required. Timber from RU reaches 14.1 MPa. As also the mean knot values of the ungraded material from RU and FR are close together for both sources, the correlation between tKAR and tension strength has been checked: For the whole dataset of pine loaded in tension, a R^2=0.47 is found. For Russian pine R^2= 0.46 while for French pine it is only R^2=0.18. Hence a reliable prediction of the strength of French pine based on tKAR seems to be impossible.

For spruce tested in tension, the differences for the ungraded material are small for different sources. The values for timber from CH, EE and SE are close together, while the timber from SI shows again higher strength values (Table 3). For the small dataset from SI, all requirements are fulfilled. Also, the grading results for the other sources are closer to the required values compared to the results for pine. The required strength values for C18-DIN and C16 for timber from SE are not reached. Eastern European timber fulfills the strength requirements, except for C30 (16.6 MPa), but fails the density requirements again. Timber from CH does not reach the strength requirements for C24-DIN (13.1 MPa) and C18 (9.3 MPa).

Comparing bending and tension, it seems more likely that required characteristic values for pieces tested in tension are met. Many deviations from the required strength values are small or can be explained. For instance, the timber from Switzerland was tested over a longer span than 9x the height, leading to lower strength values (length effect).

Conclusions

Among the three parameters, cross-sections, source of the timber, and grading standard, the latter is the most influential. The different rules of measuring knots and the number of grades in a standard influence the results. Moreover, an effect of the cross-section and the source of the graded timber have been shown to be relevant. For example, it is not possible to grade C30 with large cross-sections, because of the relevance of knot sizes and dimensions for visual grading. Grading results are similar for DIN, BS and INSTA. For sources, for which SKA data were available, the requirements are met or nearly met. Having only two grades in a standard (such as in case of BS) makes it easier to reach the required values for all possible combinations of species and type of loading. All three standards could be used for Central European timber. Reject rates are lowest for INSTA as only this standard has a grade for C 14. This trend is not transferable to high grades. Yields for C24 and higher vary from 62% for grading according to DIN to 45% for grading according to INSTA (spruce, bending). For European spruce, the characteristic values are close to the required values for all three standards, with a maximum deviation of around 10% below the required value. The absolute reject rates for visual grading vary depending on several factors, such as cross-section, grading standard and/or knot definitions. In practice, these rates will be even higher because the full board length needs to be graded, whereas in this study, only the central section has been graded. The results for NF show low yields for C30. The distinction between C24 and C18 is not really sharp. This leads to equal yields and similar characteristic values for these two grades. Hence characteristic values for C18 are met while for C24 they are not, considering CE spruce. The SIA 265/1:2009 standard leads to extreme reject rates. A practical use is not possible.

Visual grading results are clearly influenced by the source of the timber. Especially grading into C30 seems to be problematic in a number of cases. Depending on species, source and grading rules declared growth areas need clarification for a number of standards and growth areas cannot be extended without additional testing or changes in the grade limits. Allocations in EN 1912 for softwoods are not correct in a number of cases, and a review seems necessary. New limits for source areas and cross-sections are required. This can only be done based on a review of data, where the respective grading standards have proven their applicability for the listed grade, source and cross-section.

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ORIGINALS ORIGINALARBEITEN

Influence of cross-section and knot assessment on the strength of visually graded Norway spruce

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Abstract The strength of graded timber is determined by a multitude of parameters. Properties of interest are the shape of the cross-section and the wood quality. With regard to strength, wood quality is primarily expressed in terms of knots and knot clusters which, together with the cross-section of the timber, are used to calculate knot ratios. By applying the visual grading rules as given in the German standard DIN 4074-1, the influence of different timber sizes on grading results has been analysed. Different grading approaches for joists and boards exist and are taken into account in the assessment of 5,665 specimens originating from various parts of Europe. It was shown that both the cross-section and the grading method have a major influence on the characteristic strength values of Norway spruce. Limitations of the current standard with respect to its applicability to certain cross-sections are exposed. Alternative, simple grading approaches for boards are proposed. They ensure equal strength values and yields comparable to the rather complicated board rules used nowadays.

Einfluss des Querschnitts und der Bestimmung der Ästigkeit auf die Festigkeit von visuell sortierter Fichte

Zusammenfassung Die Festigkeit von sortiertem Schnittholz kann durch mehrere Parameter beeinflusst werden. Querschnittsform und Holzqualität sind hierbei von besonderem Interesse. Im Zusammenhang mit der Festigkeit wird die Holzqualität vor allem über Äste und Astansammlung, die unter Berücksichtigung des Holzquerschnitts für die Berechnung von Kennzahlen verwendet werden, definiert. Die visuellen Sortierregeln der deutschen Norm DIN 4074-1 wurden angewandt, um den Einfluss des Holzquerschnitts auf das Sortierergebnis zu überprüfen. Unterschiedliche Sortierregeln für Kanthölzer und Bretter wurden beachtet, um 5,665 Prüfkörper aus Europa zu bewerten. Sowohl die gewählte Sortierregel als auch der Querschnitt haben einen wesentlichen Einfluss auf die charakteristischen Festigkeitswerte der Rotfichte. Es wird gezeigt, dass die aktuelle Norm bei gewissen Querschnitten nur eingeschränkt anwendbar ist. Alternative und gleichzeitig schlichtere Sortierregeln für Bretter werden vorgeschlagen. Diese gewährleisten gleiche Festigkeitswerte und ähnliche Ausbeuten im Vergleich zu den momentan verwendeten, komplizierteren Sortierregeln.

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1 Introduction

Visual strength grading is widely used in Central European sawmills. On the basis of knots, growth ring widths and other visible parameters, the quality is assessed and strength, stiffness and density values are estimated by known relationships and can be used for the design process. To find out about these relationships tests are required. Stapel and Van de Kuilen (2013) have shown that in addition to the grading rule, the origin and the cross-section of the tested specimen have a major influence on the test results. For test programs planned today, the focus is rather on the origin of the timber than on the dimensions of the tested material. A detailed analysis is performed to check whether this development is justified.

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Timber engineers deal with size effects in timber since several decades. In this context, it was inevitable to also consider the visual grading: Madsen and Nielsen (1978) found that the size effect is grade dependent and stated that the size effect is less for lower grades. Madsen and Buchanan (1985) also studied size effects in timber and stated that it is difficult to separate the effect of grading rules from the effect of member size. Additionally, they expect a major influence from the way in which grading rules control defects such as knots: depending on the rules the maximum allowable defect can be an absolute or relative value. Madsen (1992) describes that by moving away from small clear specimen tests to full-size In-Grade testing a new depth factor has been introduced into the design process to allow for the differences caused by this change. A major influence resulting from the grading process was expected.

Using only a small number of samples, Fewell and Curry (1983) seem to be aware of a connection between size and quality as they consider different visual stress grades for adjustment of the depth factor, but conclude that one factor is enough for all the different qualities. In contrast, Rouger et al. (1993) found that no depth effect exists for low grades but that it is strong for high grades. French grading rules from 1946 were applied in a modified way. In an additional study on the size-effect, Rouger and Fewell (1994) also briefly addressed the relation between timber size and grading. They concluded that the size effect is considerably dependent on the visual grading method. Denzler and Glos (2008) investigated the size effect and checked the influence of the grading procedure using 517 specimens graded according to German and North American rules and tested in bending. Depending on the grading rule the magnitude of the size (depth) effect differs. Burger and Glos (1996) calculate the knot sizes according to the German DIN 4074-1. The assignment of the pieces to actual grades is used to determine the influence of the grade on a factor combining the width of the tested pieces and the test length. Large widths result in decreasing knot values, while for wide test spans larger knot values need to be considered due to the increased probability of appearing knots. The height of the specimens seems to be of minor importance.

All of these publications addressed the effect of the grading and its connection to possible size effects. In none of the studies, the grading rules were the main topic. The studies showed that the size effects are dependent on several variables which are difficult to distinguish from each other. Barrett et al. (1992) is one of the few studies that focused on size effects in visually graded softwood lumber. As for most of the other studies carried out in Northern America, the typically available cross-sections are the basis for the study. Similar to many European grading rules, the dimension lumber grades according to rules from the National Lumber Grades Authority allow larger knot sizes with increasing width of the lumber. Barrett et al. concluded from that rule that each member size may be considered to be a different material since the defect size distribution varies by width. However, size effects were shown to have a similar magnitude across grades, species and property percentile level. Length effects played a minor role.

The review of the available literature has shown that the conclusions with respect to the existence of size effect in relation to grading and test procedures differ considerably. Cross-section sizes, grading standards or the loading mode are only some of the parameters which make a difference for the single studies. Detailed analysis of the grading rules themselves are often missing, as in many studies “grading” rules are considered only as a basic parameter used for the explanation of some kind of size effect.

Not the size effect, but the grading rules themselves are in the focus of this study. It is limited to the German grading rules in DIN 4074-1 and one single species—spruce (*Picea abies*). The DIN rule was chosen as it is applied not only in Germany, but is adopted in other national standards. It is used for the major part of graded timber in Germany, Austria, Italy, Czech Republic, Slovakia and Switzerland. Therefore, no other visual grading rule in Europe is applied to a larger timber volume each year. DIN 4074-1 gives different grading rules depending on the cross-section and the intended use.

A brief historical review of DIN 4074-1 is given by Glos et al. (2002). It states that the rules for boards—which are used today—are based on an old research using a limited number of specimens. The derived maximum allowable knot values and the associated regulations for the measurements were established in 1958. Since then, only minor changes for the grading of boards were accepted. Based on 595 tension tests, Glos et al. (2002) questioned the necessity of special board rules.

There are two questions which directly arise from the described situation and should be answered by a detailed analysis of DIN 4074-1 graded timber and destructive tests:

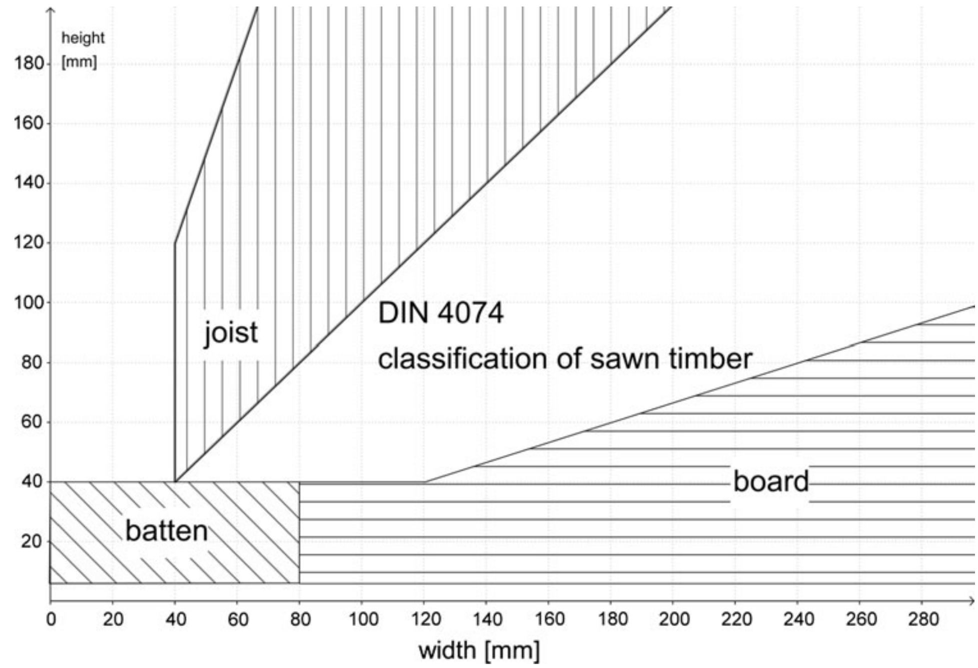
How does the cross-section influence the grading results in terms of strength properties and yield?

Is there a benefit from special grading rules for boards?

2 Materials and methods

The analysis is limited to the major European softwood species Norway spruce (*Picea abies*). A share of fir (*Abies alba*) is probably also included in the sample, as fir and spruce are and have always been traded and processed together. Sawfalling material was used for the analysis.

Fig. 1 Classification of sawn timber according to DIN 4074-1: 2012
Abb. 1 Schnittholz-Einteilung nach DIN 4074-1: 2012



The timber samples used in this analysis were tested at Holzforschung München in the course of different projects during the period between 1996 and 2012. The forests where the timber was harvested can mainly be found in Central Europe. In addition, 135 boards came from Sweden, 106 pieces from Latvia were tested. In total 5,665 tested pieces were available for the analysis.

Depending on the purpose of the project, the timber was tested in edgewise bending or tension. All destructive tests were performed according to EN 408:2010. The factors given in EN 384:2010 (k_h-factor, k_l-factor) were applied. A symmetrical two point loading was used for the determination of bending strength, usually over a span of 18 times the height. The orientation of the board in edgewise bending tests was chosen randomly. For tension tests, a span of nine times the width was usually used. Whenever possible the weakest section along the beam axis was tested.

Prior to determining the strength, the timber was visually graded according to DIN 4074-1:2012. Different sets of grading rules for joists (“Kantholz”), boards (“Brett/Bohle”) and battens (“Latten”) are included in the standard. The choice of the grading rule depends on the dimensions of the timber and its intended kind of use. While for edgewise loading of pieces the rules for joists apply, board rules are used for elements mainly stressed in tension or flatwise bending (e.g. in glued laminated timber, glued solid timber, cross laminated timber, scaffold boards, trusses with nail plates). Figure 1 shows the exact classification of sawn timber which affects the rules for measuring the knots as well as the related threshold values for the different visual grades. For this analysis, all pieces were graded according to the rules for joists. For pieces tested in tension, board rules were applied additionally. The special grading rules for battens were not taken into account.

Independent of the grading procedure (joist or board rules), pieces are classified into one of three grades or are rejected. Pieces with few or small knots are supposed to be connected with high strength values and are assigned to grade S13. Pieces with increasing knot values are assigned to the lower grades S10 or S7. If the knot values exceed a certain limit, the timber has to be rejected. Additional parameters, which were used for the classification, were growth ring width, proportion of compression wood and appearance of pith. For joists, pith is considered up to a width of 120 mm only. All grading parameters determined in the analysis are based on accurate measurements in the laboratory. The significant difference between joist and board rules is due to the rules for the knot measurement (see Fig. 2):

– For joists, the largest knot ratio of a single knot (SK) is considered for the classification. The minimum diameter *a* of the (oval) knot is independent of the face. Thus, influences caused by the angle under which the knot is sawn are excluded. Width and height are denoted *w* and *h*, respectively. Depending on the face on which the knot appears (*w* or *h*), the SK value gives the ratio between *a* and *w* or *h*.
– For boards the knot ratio is calculated from *a/w*. In this case, the size a is measured parallel to the edge of the board. More complicated rules apply in special cases. In addition to the largest knot, also the largest knot

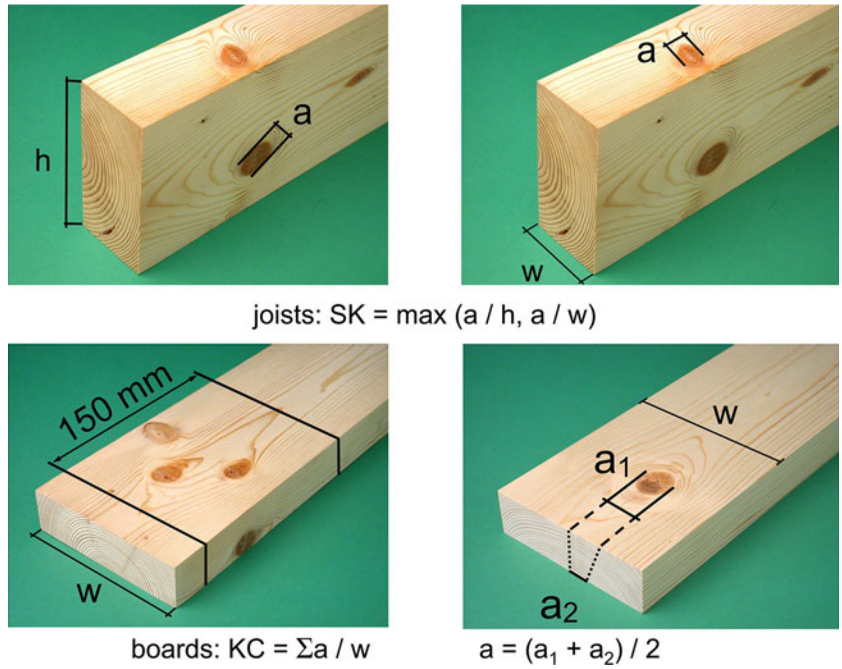


Fig. 2 Measuring rules and calculations for knots according to DIN 4074-1. *Top figures* for joists, *bottom figures* for boards (adapted from Glos and Richter 2002)
Abb. 2 Messung und Berechnung von Astwerten nach DIN 4074-1. Obere Abbildungen für Kantholz, untere Abbildungen für Bretter (nach Glos und Richter 2002)

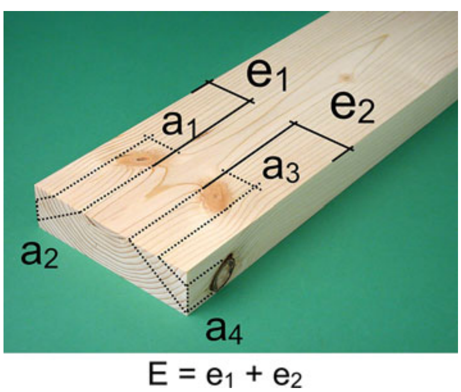


Fig. 3 Edge knot criterion for boards which are not used for glulam production Measurement of the penetration depth E (adapted from Glos and Richter 2002)
Abb. 3 Flügelastkriterium für Bretter, die nicht in der Brettschichtholzproduktion verwendet werden. Messung der Eindringtiefe E (nach Glos und Richter 2002)

cluster (KC) is considered for all knots appearing over a length of 150 mm. KC usually is the decisive grading criterion for boards. Whenever KC is addressed, the single knot measured according to board rules is also considered.

Unless the boards are used for the production of glulam lamellas, an edge knot criterion (Schmalseitenast) needs to be taken into account additionally. This criterion considers the penetration depth of the Edge knot E. Figure 3 shows how E is determined.

For joist grading, the visual grades according to DIN are linked to strength classes that are defined in EN338. EN 1912:2012 specifies these assignments. For spruce, S7 is assigned to C18, S10 to C24, and S13 to C30.

To find out a possible influence of the cross-section on strength, both joists and boards have been separated by their dimension. To keep the analysis straightforward, length effects were not considered. Although the authors are aware that length effects can influence the results (Barrett et al. 1992; Bohannon 1966; Buchanan 1990; Czmoch et al. 1991; Øvrum and Vestøl (2009), the following three arguments support this decision: (1) there are no length requirements in current standards. (2) The weakest section is placed between the loading heads for bending tests or between the jaws for tension tests. That is the section that determines the grade. (3) Most specimens had an initial length of approximately 4 m, which usually allows the weakest section to be tested in both bending and tension. Only for very large cross-sections, the weakest section cannot be placed between the load points in all cases.

The influence of the cross-section on the grading results can be analysed on the basis of the width (1), the height (2), a cross-sectional area (3) or a combination of these parameters (4). The problem with analysing combinations is the size of the dataset. Breaking down the respectably sized data basis leads to very small samples within the different grades that do not allow calculations of significant characteristic values. Hence, the correlations between the parameters 1–3 and the knot values for joists and boards were checked separately in order to decide on which criterion is most suitable to form classes. The highest correlation has been found for the width and knot value for both

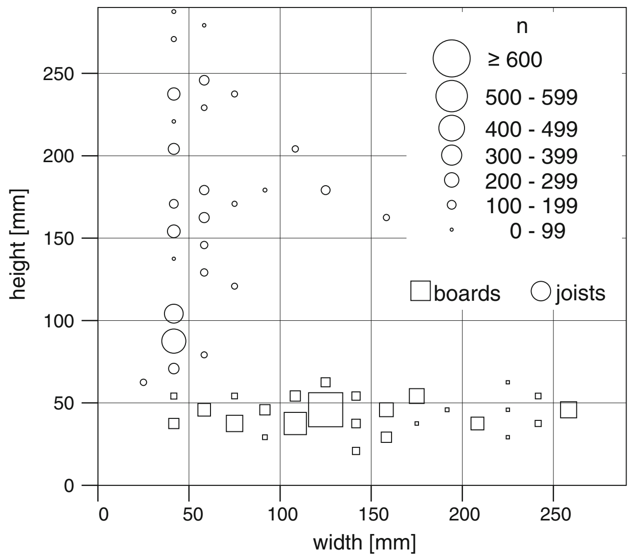


Fig. 4 Overview of the tested cross-sections
Abb. 4 Überblick über die geprüften Querschnitte

joists and boards. Thus, for joists the smaller dimension is more important and for boards, the larger dimension as indicated in Fig. 1. For each of the two loading modes, six classes were formed. An overview of the available cross-sections is given in Fig. 4.

The width of the boards ranged between 44 and 263 mm. Table 1 shows that the number of pieces in each group is approximately equal. Table 1 also gives mean values, coefficients of variation (COV) and 5th percentile values for MOR, MOE and density. As indicated in Fig. 1, the smallest width class 44–79 mm is not a cross-section which is supposed to be graded using board rules. As this can be done anyhow, the cross-section was included in the analyses in order to find out about the applicability of board rules for these widths. For joists, fewer pieces with very small and very large widths are available. The widths range between 20 and 166 mm.

Mean values and coefficients of variation for strength, stiffness and density are given for the ungraded timber for the total sample as well as separated by height. Except for MOE, 5th percentile values are also listed. 5th percentile values were calculated assuming a non-parametric distribution in accordance with EN384.

For the production of glulam, the height of the lamellas needs to be between 6 and 45 mm (EN 14080:2005). 1958 of the tension specimens fulfil this requirement, while 1260 exceed the allowed height. Verification is performed to check whether this has a major influence on the grading or not.

During the analysis of the data, focus was put on strength values. As an indicator for the expected strength values within one grade, strength values are calculated neglecting the breakdown by dimension. To judge the effectiveness of the grading, the yield is used as an indicator.

Due to the results from the different grading options (using E or not) for boards, the rules for boards were examined in detail. E was introduced in the third edition of

Table 1 Strength, stiffness and density properties for ungraded timber
Tab. 1 Festigkeits-, Steifigkeits- und Dichteeigenschaften des unsortierten Holzes

Width (mm)	n (–)	MOR			MOE		Density		
		Mean (MPa)	COV (–)	5th (MPa)	Mean (MPa)	COV (–)	Mean (kg m^{-3})	COV (kg m^{-3})	5th (MPa)
Bending									
20–166	2,447	39.2	0.33	19.4	11,600	0.26	439	0.12	364
20–35	123	37.8	0.41	13.8	12,000	0.36	457	0.16	349
36–38	588	36.0	0.34	16.7	11,100	0.27	438	0.12	360
39–49	674	39.2	0.34	20.7	11,900	0.25	447	0.11	374
50–65	692	40.9	0.31	22.1	11,700	0.25	435	0.12	358
79–109	212	42.1	0.31	21.1	11,800	0.24	430	0.10	363
127–166	158	40.8	0.25	25.2	10,700	0.18	431	0.08	374
Tension									
44–263	3,218	30.3	0.40	14.2	11,500	0.23	448	0.11	370
44–79	571	29.3	0.36	14.9	11,100	0.22	456	0.10	379
80–108	615	28.1	0.38	13.9	10,800	0.23	440	0.12	361
114–125	454	31.5	0.37	15.8	11,600	0.21	448	0.11	372
126–150	548	28.6	0.44	12.3	11,200	0.25	441	0.12	363
151–177	505	31.9	0.41	14.2	12,400	0.23	457	0.12	374
199–263	525	33.2	0.38	15.7	12,300	0.19	450	0.10	382

Table 2 Yield, strength, stiffness and density values for graded timber
Tab. 2 Ausbeute-, Festigkeits-, Steifigkeits- und Dichtewerte des sortierten Materials

Load mode	Rules for	Grade (–)	n (–)	Yield %	MOR			MOE		Density		
					Mean (MPa)	COV (–)	5th (MPa)	Mean (MPa)	COV (–)	Mean (kg m^{-3})	COV (–)	5th (kg m^{-3})
Bending	Joists (SK)	S13	287	12	48.8	0.26	28.7	13,200	0.23	460	0.11	387
		S10	1,225	50	42.3	0.29	22.8	12,100	0.24	440	0.12	363
		S7	697	28	33.6	0.29	19.1	10,700	0.23	432	0.11	361
		Reject	238	10	27.9	0.39	9.2	9,500	0.29	434	0.13	352
Tension	Lamellas (KC)	S13	674	21	40.7	0.33	21.9	13,600	0.19	474	0.11	392
		S10	1,786	56	29.4	0.34	15.2	11,400	0.2	444	0.11	367
		S7	502	16	23.9	0.34	12.5	10,100	0.2	437	0.11	367
		Reject	256	8	22.2	0.36	11.1	9,700	0.24	437	0.12	358
	Boards (KC&E)	S13	484	15	41.3	0.32	22.6	13,600	0.19	473	0.11	393
		S10	1,326	41	30.1	0.36	15.4	11,700	0.21	448	0.11	368
		S7	1,152	36	27.8	0.37	13.6	10,900	0.21	441	0.11	368
		Reject	256	8	22.2	0.36	11.1	9,700	0.24	437	0.12	358

DIN 4074-1 from 1989 (DIN 4074-1:1989). Glos et al. (2002) expected probably a different effect of E between boards tested in tension and boards tested in bending, as both cases were tested. No such difference could be shown. Today, E is still used for all boards, except for boards used for the production of glulam.

It was tried to simplify the board grading by adjusting the currently used rules for joists and boards. The following options were tested:

1. Alternative board rules—not considering E
2. Using joist rules for boards—“joist unchanged”
3. Using adjusted joist rules for boards—“joist alternative”

3 Results and discussion

3.1 General grading results

Before taking into account the effect of cross-sections and discussing alternative grading approaches, the plain grading results are discussed. Table 2 shows the yield, strength, modulus of elasticity, and density values for the graded timber. Comparing the relation between strength and stiffness with the ratio resulting from the values given in EN 338:2010, it was noticed that MOE values are relatively high. The same is true for density values. Hence, for the assignment of visual grades to strength classes, the strength would be the most critical value and will be used as the essential parameter to judge the current grading results. MOE and density are going to be addressed briefly. In order to keep an eye on the economic efficiency, the yield needs to be considered as a second important parameter.

The grading results show that the major part of the timber is graded as S10. Reject rates independent of the grading procedure are about 10 %. The COV within the single grades is smaller for the grading of joists (SK) compared to the grading of lamellas (KC) or boards (KC + E).

By using joist rules, considerable differences in terms of strength and MOE values for different grades can be reached. A reasonable separation of the ungraded material is possible. A distinction with regard to density values can only be made between S13 and lower grades. Only minor differences are found between S10 and S7.

Comparing the two possible grading options (using only KC or KC&E) for pieces tested in tension, the additional edge knot rule for boards leads to lower yields in the higher grades. Reject rates do not change as there are no requirements on the edge knot for S7. Differences in the 5th percentile strength values are small. The highest difference is reached for S7 with 1.1 MPa. For S10, the difference is 0.2 MPa. For S13, the additional knot edge criterion leads to a strength of 22.6 MPa, while without that 21.9 MPa is reached. Looking at these differences it may be questioned whether this minor increase in strength values justifies the significantly lower yields.

Let us have a closer look at the grading results for tension members. As mentioned before, EN 14080 only allows heights up to 45 mm for lamellas to be used in GLT (glued laminated timber) beams. The authors wanted to check whether this constraint is important for the strength of the single lamellas and whether it needs to be considered already during grading. Therefore, the results shown in

Table 3 Tension strengths and yields for different grading rules separated by height
Tab. 3 Zugfestigkeitswerte und Ausbeuten für unterschiedliche Sortierregeln und Höhen

Height (mm)	Grade (–)	Lamella rules (KC)					Board rules (KC&E)				
		n (–)	Yield %	MOR			n (–)	Yield %	MOR		
				Mean (MPa)	COV (–)	5th (MPa)			Mean (MPa)	COV (–)	5th (MPa)
<=45	S13	392	20	41.8	0.34	21.9	299	15	43.0	0.33	23.0
	S10	1,045	53	28.0	0.35	14.0	826	42	28.5	0.36	14.0
	S7	341	17	23.2	0.35	11.5	653	33	26.2	0.38	12.6
	Reject	180	9	21.3	0.36	11.1	180	9	21.3	0.36	11.1
>45	S13	282	22	39.0	0.31	21.7	185	15	38.6	0.30	22.0
	S10	741	59	31.4	0.33	17.2	500	40	32.6	0.35	18.0
	S7	161	13	25.4	0.33	14.1	499	40	29.9	0.35	15.0
	Reject	76	6	24.2	0.36	10.4	76	6	24.2	0.36	10.4

Table 2 are divided by the height of the specimens (Table 3). If the trends observed for the undivided dataset also occur for the dataset which was divided by the height, the data for boards can be analysed for all heights together:

The differences between the undivided and the divided data are small. The largest deviation from the undivided data—with respect to yield—is found for heights above 45 mm using KC&E in grade S7. A yield of 40 % instead of 36 % is reached. Due to the close relation between the grades, it makes no sense to distinguish these two different grading options as the influences on strength or yield are negligible. Variation in visual grading quality show larger scatter in results anyhow (Stapel and Van de Kuilen 2013). The effect on the tension strength values observed for the different rules are similar for the dataset separated by height and the combined dataset. A combined analysis of the dataset is, therefore, possible.

Nevertheless, an influence caused by the height can be recognized by simply comparing the values for the two height groups in Table 3. This can be observed for both grading options. For small heights, the tension strength values for the S10 dataset (KC&E: 14.0 MPa, KC: 14.0 MPa) decrease compared to the value for the combined dataset (Table 2, KC&E: 15.4 MPa, KC: 15.2 MPa), while they increase for large heights (KC&E: 18.0 MPa, KC: 17.2 MPa). The reversed effect was found for S13. Strength values for small heights are higher. Large heights show relatively lower strengths.

3.2 Joists

Figure 5 shows the importance of the width for the grading results of joists. The so called SK (Fig. 2) turns out to be the crucial grading parameter for the classification. The resulting grades are indicated by different colours and symbols. The thresholds for this parameter are obvious—values of 0.2, 0.4 and 0.6 subdivide the sawfalling population.

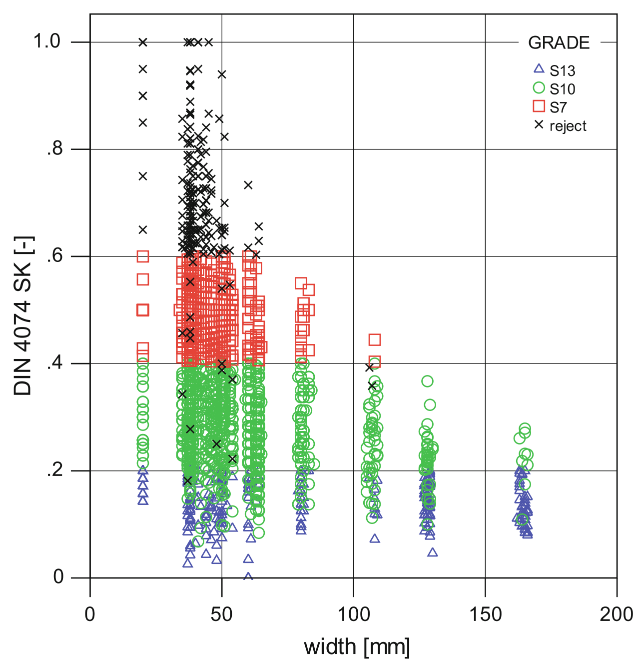
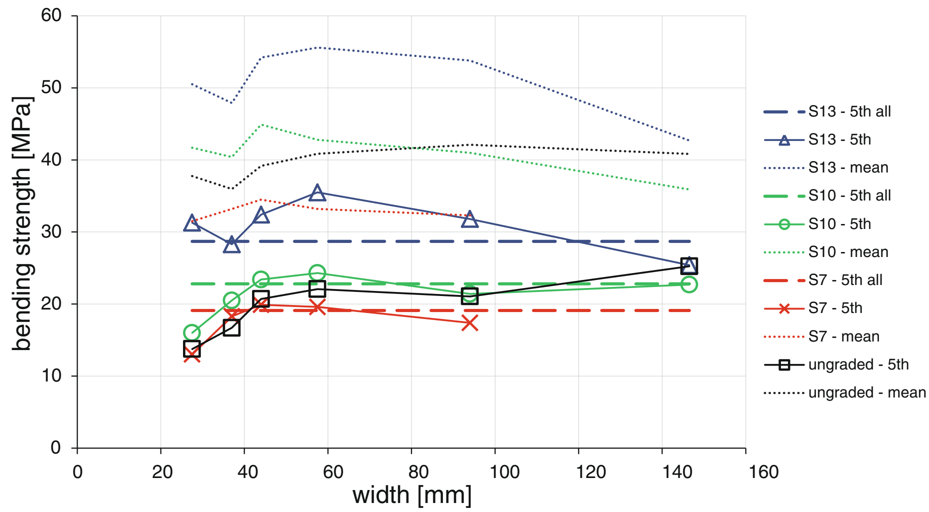


Fig. 5 Grading parameter SK for joists plotted over the width. n = 2,447
Abb. 5 Kantholzsortierparameter SK über die Breite. n = 2.447

A maximum SK value of 1.0 is caused by a knot which, with its smaller diameter, covers the complete height or width of a specimen. Values of 1.0 are reached up to a width of slightly below 50 mm. With increasing widths, the maximum knot value is decreasing. When the knot values are considered over all widths, no SK value was found representing a knot where the smallest diameter is larger than 50 mm. This is apparently a biological limit of the knot size and is directly influencing the grading results.

Fig. 6 Bending strength for joists over width classes for different visual grades
Abb. 6 Biegefestigkeit für Kanthölzer über Breitenklassen unterteilt nach Sortierklassen



For widths above 50 mm, the share of timber being rejected is negligible. Timber with widths of 100 mm and more shows, if at all—only few pieces of S7. A further increase of the width goes along with a decreasing share of S10 and more assignments to S13.

After knots, pith is the second most important parameter for excluding a specimen from being assigned to grade S13. With increasing size of the cross-section, the authors expect to find more and more pieces with pith. This effect (increasing share of round green dots below a SK of 0.2) can be followed up to a width of 120 mm. Higher widths result in a higher share of S13 for pieces with a knot value below 0.2, as—according to DIN 4074-1, pith is no reason for downgrading of these dimensions.

Figure 6 shows the trend for the strength values for different widths categories. Results are given for all three grades and the ungraded timber. Dotted lines stand for the mean value, while all other elements in the Figure are used for the 5th percentile values. The dashed lines are drawn at the height of 5th percentile strength given in Table 2. Thus, they represent the 5th percentile strength values resulting from the analysis for all widths.

For the interpretation of the results shown in Fig. 6, the total number of specimens available for each width class and the allocation of the available specimens must be considered. The number of pieces for width classes between 36 and 65 mm are sufficient. The width class 20–35 mm contains 123 specimens only. The classes 79–109 and 127–166 mm contain 212 and 158 specimens, respectively. Still, the results are reliable enough as the pieces are mainly divided into two grades; less than 7 % of these pieces are graded into S7 or are rejected.

The highest and the lowest width class clearly show a different behaviour to the classes in between. Especially critical are the 5th percentile bending strength values for S10 of 15.3 MPa for the lowest width class and the low strength for S13 of 25.4 MPa for the highest width class. Obviously, the grading rules do not match the challenge of very small or very large cross-sections. The reason for the low bending strength of S10 may be found in the low frequency of the appearance of knots on the edge of the joist.

Table 4 Yields in percent for joists over different widths for different visual grades
Tab. 4 Prozentuale Kantholzausbeuten für unterschiedliche Breiten und Sortierklassen

	Width (mm)					
	20–35	36–38	39–49	50–65	79–109	127–166
Grade						
S13	14	6	5	7	17	73
S10	43	41	42	65	72	27
S7	26	38	37	25	10	0
Reject	17	15	15	3	1	0

While one can only speculate about the reason for the low strength values for small widths, the reason for the low strength of large sized S13 joists seems obvious. It can be found in the combination of maximum knot diameter and minimum cross-section of the joist together with the disregard of the pith. This causes the major part of the timber to be graded as S13. Hence, the strength value for the graded timber does not differ from the ungraded timber and is clearly below the average value of the 5th percentile over all width classes.

Values for S7 are in the range of values for ungraded timber. Values for S10 are usually clearly above. The difference between the strength values of S7 and S10 is usually far less than 6 MPa as one would expect from the assigned corresponding strength classes C18 and C24. On the other hand, the distance between S13 (C30) and S10 (C24) is larger than expected. Not considering the values for the largest widths class, the distance is between 7.8 and 15.3 MPa.

Figure 5 already allowed an estimation of the coherence between width and visual grades. In Table 4 exact shares per width class are given. Leaving the smallest width class out, the share of S7 and reject is decreasing with increasing width. This causes high shares of S10 and S13 for the larger widths. For the largest widths, an enormous share of S13 was found.

Combining the yields with the connected strength, the increasing yield of S10 is not connected to decreasing strength values. This is not true for S13 in the highest width class. With 73 % of the pieces in that grade, the high strength requirement cannot be fulfilled, as the ungraded material in that width class has not much higher mean strength values compared to other width classes (Fig. 6).

As mentioned before, the high share of S13 in this width class is caused by neglecting the pith criterion. Using it also for a width above 120 mm might be a simple solution for the problem. If the criterion is used, the yield figures show a reaction. The yield for S13 drops from 73 to 28 %. Unfortunately, this has no effect on the characteristic values. The strength value on the 5th percentile level shows no reaction, and the mean value even decreases. Grading joists with a width above 120 mm is not sensible using the rules given in DIN 4074-1. Knot sizes or the presence or absence of pith do not influence strength values. Due to the high mean strength and the low strength variation of the ungraded material, these sizes can be assigned safely to S10.

For MOE and density, the influence of the width class is small. MOE and density values are relatively constant over all classes. For the grading results shown in Table 2, it was stated that the characteristic values for MOE and density are above the requirements. Except for the density value for grade S10 for width class 44–79 mm and the MOE values for grade S10&S13 for width class 127–166 mm the required characteristic values according to EN 338 are reached. While the deviation in density is small, MOE values are at least 800 MPa below the requirement.

3.3 Boards

The grading rules for boards lead to a different picture of the grading results. Figure 7 shows the results for board grading and corresponds to Fig. 5 which is used to explain the effects of joist grading rules. For the grading of boards, however, different parameters are used. That is the reason for KC values above 1.0. This knot value aggregates knot values over a length of 150 mm. For pieces classified as

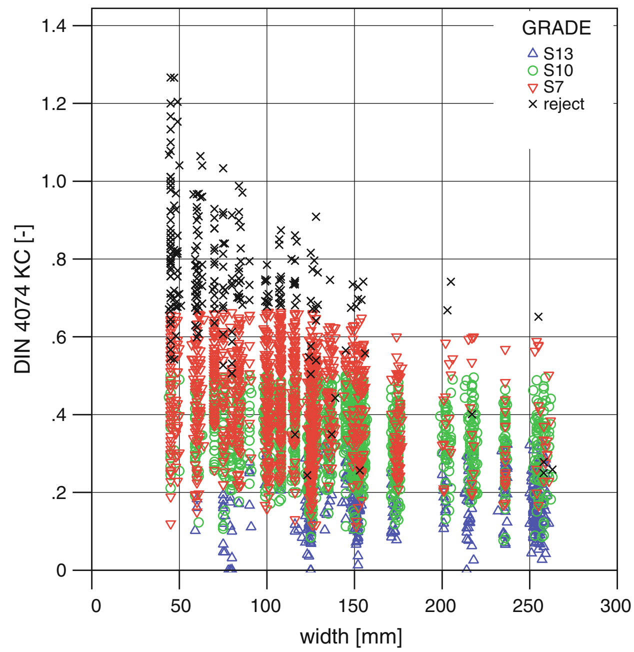


Fig. 7 Grading parameter KC for boards plotted over the width. n = 3,218

Abb. 7 Brettsortierparameter KC über die Breite. n = 3.218

boards (Fig. 1), knot values larger than 1.0 are not present in this dataset. Knot values reaching larger values are found only for battens graded with board rules. Other knot values, such as the edge knot measured besides the KC, have a major influence on the grading results. This can be easily seen by the increased mixture of different grades for certain KC values. While a SK value between 0.2 and 0.4 results in grade S10 for almost all joists (Fig. 5), it is hard to predict the final grade for boards from a KC value between 0.33 and 0.5 (Fig. 7). For the joist grading, the SK value is ever increasing with increasing joist widths, this is only true up to a point for the KC value. For widths between 170 and 270 mm, KC values remain fairly constant. Over the complete range of widths from 44 to 263 mm, the percentage of reject and S7 seems to decrease, while it increases for S10 and S13.

Figure 8 compares the tensile strength values for different width classes. As mentioned before, the smallest width class 44–79 mm includes cross-sections usually used as battens. This is the only cross-section where the 5th percentile value of a lower grade (S10) is above the value for the next higher grade (S13). Describing the major influence of the width, one can compare the two remaining smaller classes 80–108 and 114–125 mm to the three higher ones. The main difference can be found for shifts in 5th percentile strength values between visual grades S10 and S13 for the different width classes. While for the small width classes, the difference between S10 and S13 never exceeds 1.0 MPa, differences up to 10.9 MPa are found for

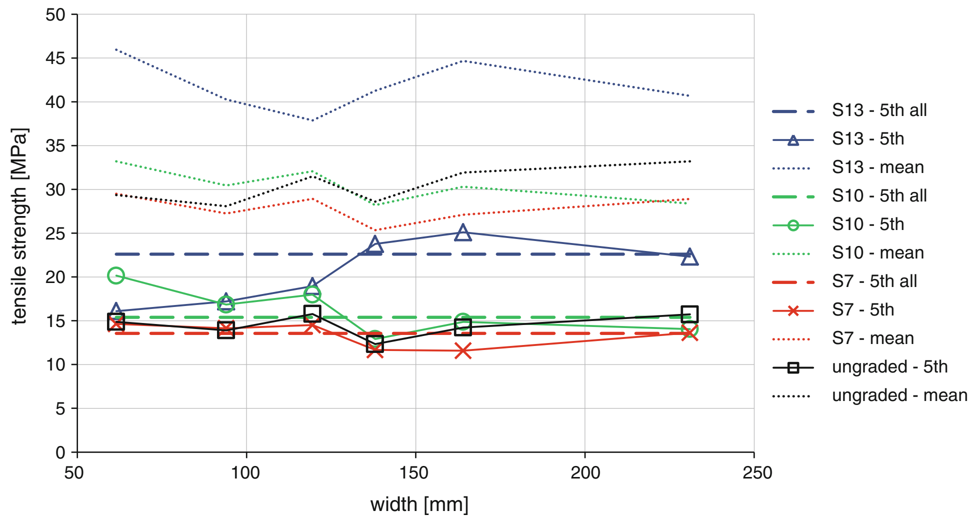


Fig. 8 Tensile strength over different widths for different visual grades according to board rules (KC&E)
Abb. 8 Zugfestigkeit über Breitenklassen unterteilt nach Sortierklassen für Brettregeln (KC&E)

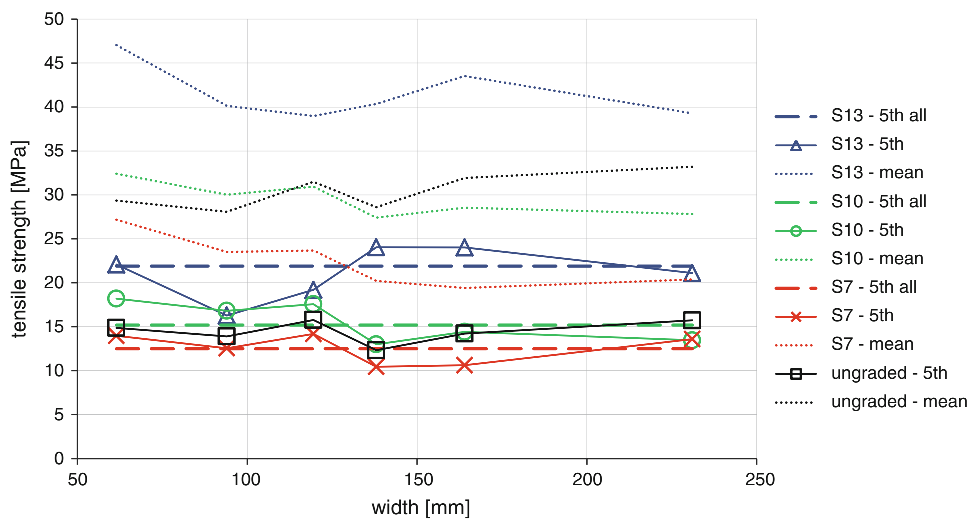


Fig. 9 Tensile strength over different widths for different visual grades according to GLT rules (KC)
Abb. 9 Zugfestigkeit über Breitenklassen unterteilt nach Sortierklassen für BSH-Regeln (KC)

larger widths. Differences between the grades S10 and S7 for all classes are close to 1.8 MPa—equal to the difference between S10 and S7 for the undivided dataset (Table 2). Comparing the grading results for the undivided dataset to the results for smaller widths, too low values for S13 are found. For larger widths an inverted effect turns out.

Table 2 lists grading results for different grading rules. The choice of the rule caused only minor differences in terms of characteristic values for grades S10 and S13. Differences resulting for different heights were expected, and the data was additionally analyzed as to that. However, Table 3 shows that no such differences exist. Still, there might be an influence caused by different widths. Whether neglecting the edge knot criterion actually influences the grading result is shown in Fig. 9. It does not. Figures 8 and 9 have only two minor differences. The first one can be found for the smallest width class. Unlike in Fig. 8, the 5th percentile strength value for S10 is not higher than the one for S13. The second difference can be found for the values of grade S7. In Fig. 9, they are lower over all classes. Generally, considering all width classes, differences in strength values are very small.

However, there are considerable differences in the yields between the two grading options. Table 5 gives the yields for boards using the edge knot criterion and shows the yields resulting from the special rules for the production of glulam lamellas.

The share of S7 and reject shrinks with growing width independent of the grading option. The opposite trend can be observed for higher grades. Again, the edge knot criterion has no influence on the relative reaction to width.

Connecting the yields with the corresponding 5th percentile strength values, it can be seen that high yields do not necessarily cause low strength values and vice versa. Looking at the results for GLT rules (KC) within the width class 80–108 mm, a yield in grade S13 of only 6 % was

Table 5 Yields in percent for pieces tested in tension over different widths for different visual grades according to board (KC&E) and GLT rules (KC)

Tab. 5 Prozentuale Ausbeuten für Zugprüfkörper für unterschiedliche Breiten und Sortierklassen nach Brett- (KC&E) und BSH-Sortierregeln (KC)

	Grade	Width (mm)					
		44–79	80–108	114–125	126–150	151–177	199–263
Boards (KC&E)	S13	3	3	16	14	18	39
	S10	22	37	43	48	53	47
	S7	48	51	37	36	27	12
	Reject	27	9	4	3	1	1
GLT-lamellas (KC)	S13	5	6	22	20	28	50
	S10	38	62	61	63	64	46
	S7	30	23	13	15	7	3
	Reject	27	9	4	3	1	1

obtained and a tensile strength of 16.3 MPa was reached, but half of the timber is graded in the highest grade for the largest width class and is resulting in a strength value of 21.1 MPa.

Absolute yields do react on the chosen grading rule. The values over all width classes are given in Table 2. Considering the grades S13 and S10 together, the yield using GLT (KC) rules is 20 % higher in comparison with board rules (KC&E). Applying this comparison to different width classes, a difference of 28 % for the width class "80–108 mm" is obtained. With increasing widths, the differences in yield are decreasing. A minimum of 10 % can be found in the largest width class.

The grading practice of boards can be summarized as follows:

The additional edge knot criterion leads to a minor increase in S10 and S13 strength values. This strength increase is disproportional to the decrease in yield.

Independent of the criteria used, a strong influence from the width can be noted on the strength and on the yield. Depending on the width of the product, assignments or expected strength values need to be adjusted for board grading rules. A shift can be observed at a width of 125 mm. For widths below 125 mm, grading into S10 and S13 is ineffective as characteristic values are almost the same for both grades. Here, grading into one grade only—S10 and better—would make more sense without compromising the strength value. If the width of the board exceeds 125 mm, a different picture is obtained. Strength values for S10 and S13 are far apart. Strength values for S13 increase, while the values for S10 and S7 decrease.

For MOE and density of boards, the influence of the width class is smaller compared to joists. MOE and density values are constant over all classes. No extreme values are found.

3.4 Adjusted grading rules for boards

Opposing the huge differences in yield to the minimum gain in strength, the authors just questioned the use of the rather complicated grading criterion "edge knot". If the minor increase in strength resulting from the edge knot criterion is really needed, the question is: Could the same strength values be reached if the threshold values for the standard knot criterion were adjusted?

This is already a process of simplifying the grading rule. The additional question, which arises, is also obvious: As the yields for the grading of boards using all criteria are low, would the strength and yield values be worse when the simple joist grading rules are applied to boards? Is it required to adjust the knot values when joist grading rules are used for boards?

3.4.1 "Board alternative" rules

To turn down the "edge knot" E and choose other threshold values for the knot value is probably the less radical of the two approaches. It is labelled "board alternative". Knot values for KC were checked out which might also be applicable in practice (e.g. 1/10, 1/5, 1/4, 1/3). The decision for the use of a knot value is based on the resulting characteristic strength. For S13, for example, a 5th percentile tension strength value of 22.6 MPa results from using board rules with KC&E (compare Table 2). This strength can be reached using a KC value of 1/4. Compared to the board grading rule for which the edge knot is used as an additional parameter the yield is unchanged. Yields, strength and knot values are given for all grades in Table 6. While a slightly higher characteristic strength for S10 is reached by the use of the "board alternative" rule, the yield increases from 41 to 62 %.

Table 6 Grading of boards according to newly established knot values

Tab. 6 Sortierung der Bretter nach den neu festgelegten Astwerten. KC wird für die angepassten Brettregeln, SK wird für die beiden Kantholzregeln verwendet

Rules	Grade (–)	n (–)	Yield %	MOR			Knot value (–)
				Mean (MPa)	COV (–)	5th (MPa)	
Board alternative	S13	472	15	42.7	0.32	22.6	1/4
	S10	1,988	62	30.1	0.34	15.5	1/2
	S7	502	16	23.9	0.34	12.5	2/3
	Reject	256	8	22.2	0.36	11.1	–
Joist unchanged	S13	267	8	43.4	0.35	21.9	1/5
	S10	1,541	48	33.3	0.34	17.2	2/5
	S7	1,082	34	25.7	0.32	13.4	3/5
	Reject	328	10	20.9	0.36	10.6	–
Joist alternative	S13	645	20	40.2	0.33	22.0	1/3
	S10	1,867	58	29.8	0.35	15.7	1/2
	S7	498	15	23.7	0.33	12.5	2/3
	Reject	208	6	19.9	0.37	9.9	–

KC is used for the "board alternative" rule. SK is used for the two joist rules

These 21 % are no longer graded as S7 and therefore, can no longer contribute to the distribution of strength values within that grade. The S7 characteristic value decreases from 13.6 to 12.5 MPa. This alternative grading rule would be easier to use as no edge knot value is required. Concerning the strength, no reductions were found for S10 and S13 and large profit in yield can be expected for the important grade S10.

3.4.2 *Joist rules used for board grading*

Table 6 shows what happens when the simple grading rule for joists (SK) is applied to boards. The tested options are labelled "joist unchanged" and "joist alternative". "Joist unchanged" means that the grading rules given in DIN 4074-1 for joists were used to grade the 3,218 boards using also the threshold knot values given in the standard. For "joist alternative", the grading rules were adjusted to allow for the different width to height ratios for boards.

Let us have a closer look at the results for "joist unchanged" first. The yields for S13 are low, but with a characteristic strength of 21.9 MPa, the strength matches the strength obtained for boards graded according to GLT-lamella rules. For S10, the yield is reasonable and due to the low yield in S13 above the values obtained with the current board rules. The grading of S7 results in a high characteristic strength value of 13.4 MPa. The reject rate of 10 % corresponds to the reject rate obtained for the grading of joists and is, therefore, 2 % above the reject rate obtained from board rules.

3.4.3 *"Joist alternative" rules used for board grading*

Instead of using a SK value of 1/5 for S13, larger knots up to knot sizes of 1/3 were allowed for in the "joist alternative" rule. This value was established in two steps: During the first attempt, the authors tried to reach a characteristic strength value of 22.6 MPa which can be reached using the KC knot value. This is not possible when only the SK value is used. In the second step, the knot size was increased. As the first target strength value was not feasible, at least the strength resulting from the lamella rules should be met. A SK value of 1/3 allows for the according strength value of 21.9 MPa. With SK values of 1/2 for S10 and 2/3 for S7, strength values are around the values resulting from board rules. These values correspond to the values given by Glos et al. (2002), based on a much smaller dataset. What surprises is the fact that the yield using SK is not lower compared to board rules. On the contrary, SK rules lead to lower reject rates. As the differences between all board rules (using KC) and the "joist alternative" rules (SK) in terms of strength are small, it is questionable whether the general differentiation between the grading of joists and boards is necessary. "Joist alternative" rules give similar yields. In real life, the differences might be even smaller as the joist rules are probably easier to apply and therefore, can lead to a more accurate grading result.

3.4.4 *"Joist alternative" rules: influence of the width*

The influence of the width on the grading result has already been checked and discussed for the current

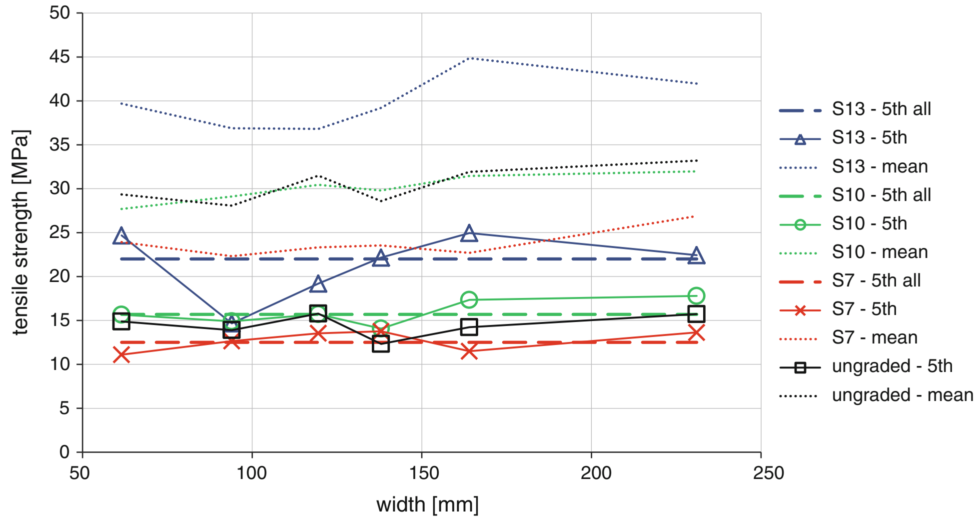


Fig. 10 Tensile strength over different widths for different visual grades according to "joist alternative" rules
Abb. 10 Zugfestigkeit über Breitenklassen unterteilt nach Sortierklassen für angepasste Kantholzregeln

Table 7 Yields in percent for pieces tested in tension over different widths using the "joist alternative" rules (SK)
Tab. 7 Prozentuale Ausbeute der Zugprüfkörper über unterschiedliche Breitenklassen bei Verwendung der angepassten Kantholzregeln (SK)

Grade	Width (mm)					
	44–79	80–108	114–125	126–150	151–177	199–263
S13	18	8	31	16	22	30
S10	69	68	56	54	52	46
S7	12	21	10	17	15	16
Reject	1	3	3	13	11	8

grading rules (Figs. 8, 9). It was found that the use of E has only a minor influence on the strength values. This might of course change, when only SK is used for the grading of boards. Therefore the analysis is repeated for the joist alternative rule. The results are shown in Fig. 10. Strength values differ only slightly from the values currently obtained. The main difference can be found for S10. Now, the two highest width classes show values above the mean value for this grade, which was not the case in Figs. 8 and 9.

For the yield, differences are found when analysed for width classes (Table 7). The share of reject for the lower width classes is reduced to a maximum of 3 %. In contrast, the reject rates increase by up to 10 % for higher width classes. Also the share of S7 increases for these width classes. The high share of rejects and S7 obtained when using joist alternative rule is leading to a higher quality of S10 and S13 boards.

3.5 Comparison

For a possible revision of the standard, inclusion of the "joist alternative" rule would offer a good option for the grading of boards as it gives similar results compared to board rules (except for the lower yield of large cross-sections). To set up grading rules based on the single knot would also simplify the visual grading process performed by automatic grading devices using images.

What is lacking so far is to interpret the results with respect to the size effect which was the heart of so many studies mentioned in the introduction. This will happen in a rather basic way. The course of the strength over the widths for the ungraded timber is shown in Figs. 6, 8 and 9. All of the values shown there already include the height factor k_h given in the standard. Anyway, this fact is of minor interest as it is used for ungraded as well as graded timber. While for joists, increasing strength values might be expected with increasing width, no clear trend can be found for boards. Certainly, a big influence caused by the grading can be stated which is influencing the results depending on the height in an almost unpredictable way.

To assume a consistent size effect for timber seems bizarre. Different species, grades, grading rules, sawing patterns are all influencing the material which is put on the market. It is reasonable to assume that a careful investigation is necessary for the possible combinations of interest. For all other combinations, turning the size effect down seems to be the better choice.

This concludes the discussion and allows comparing the current results to the results listed in literature. The basic fact that the grading method is influencing the strength values as a function of width is certainly true (Madsen 1992; Rouger and Fewell 1994). However, it cannot be supported that no such connection exists for low grades (Rouger et al. 1993) which were found for the French grading rules. Also, one factor as proposed by Fewell and Curry (1983) is not enough to cover the effect of all different qualities. Thus, the statement from Barrett et al. (1992) who expand the consistency of size effects from being consistent across grades to species and percentile level may not be supported based on the results of the current study. Only for the grading of joists, the size effect seems less for lower grades (Madsen and Nielsen 1978). For boards, lower grades strongly react to the width.

For a certain strength class, the influence of the width on the variation of characteristic values can be larger than the influence of the source. As shown by Stapel and Van de Kuilen (2013), the range of 5th percentile strength values for C24 (S10) varied between 23.2 and 25.4 MPa. For C30 (S13), the deviation between sources was shown to be much higher, but this might have been partly biased because of the low number of specimens for some sources.

The joist grading results can be directly compared. Excluding the smallest width class, values between 20.5 and 24.3 MPa can be found for S10. For characteristic strength values for S13 a minimum of 25.4 MPa and a maximum of 35.5 MPa is possible. For tension, S10 values can be as low as 12.9 MPa and as high as 18.0 MPa. For S13, values differ by up to 8 MPa. These numbers prove that for deriving characteristic strength values for visually graded timber it is at least as important to cover the strived cross-section range as to test timber from different sources. For a safe assignment of characteristic strength values, it is necessary to analyse the data separated by dimension.

If high quality timber from a certain source and beneficial cross-sections are combined, the chance of overrated strength class assignments in EN1912 is increasing.

4 Conclusion

An in-depth analysis of the German visual grading standard DIN 4074-1 was carried out with respect to the influence of cross-sections and the different grading approaches for joists and boards. The research results indicated that a major influence of the cross-section is present. This contrasts the design of current test programs for the assignment of visual grades to characteristic strength values where this influence is hardly considered.

Yields and strength values show considerable differences depending on the width. The grading rule has a major influence on so called size effects. If size effect factors are introduced and are supposed to be used, it is necessary to carry out a careful investigation considering the influencing parameters. First of all, the grading rule needs to be taken into account. Unless this is done, no size factors should be used to correct strength values based on timber width.

Above a width of 120 mm, the grading of joists is not feasible using DIN 4074-1, however, the ungraded material can be assigned to S10 (24.0 MPa).

When characteristic values are derived for a visual strength class, it is necessary to check strength values separately for different cross-sections as a stronger influence is found compared to the influence caused by the timber source.

It was checked whether it is necessary to have different grading approaches for joists and boards as considered in DIN 4074-1.

It was shown that there is only a minor increase in strength, but yields are far lower when the additional parameter E for the grading of boards is considered. If actually slightly higher strength values are required for a product, a slight increase in the threshold value used for the basic method would deliver comparable strength values without decreasing the yield. Boards tested in flatwise bending were not used in this analysis. As it was shown that no influence from E is to be expected for boards loaded in tension, it should not be mandatory for boards unless they are used in special flatwise bending applications (e.g. scaffold boards). Even the easy to use grading rule which is so far limited to joist grading could be used for grading boards by a slight adjustment of threshold values.

For a possible revision of DIN 4074-1, the joist grading option should be considered with threshold values of 1/3, 1/2, 2/3 for spruce in strength classes C18-C24-C30, respectively. For this revision, taking into account the presented results would allow for easier grading rules and higher yields.

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III

INTERNATIONAL COUNCIL FOR RESEARCH AND INNOVATION IN BUILDING AND CONSTRUCTION

WORKING COMMISSION W18 - TIMBER STRUCTURES

INFLUENCE OF SAMPLE SIZE ON ASSIGNED CHARACTERISTIC STRENGTH VALUES

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THE NETHERLANDS

MEETING FORTY FOUR
ALGHERO
ITALY
AUGUST 2011

Presented by P Stapel
J Köhler questioned about 1) the confidence intervals to the design of the structure an 2) whether each subsample would be expected to have the target strength values.
P Stapel answered that question 2 should be directed to the users as to what would be their expectations. J W van de Kuilen added that on average one would like to see the samples meet the target level; however, this could not be checked if there was not enough data. Also the checks needed to be done based on the limited available data and this did not have to do the design issues.
F Rouger asked whether the approach of Ks or CI and Weibull based for 5%tile calculations in relation to the stability of small sample size.
P Stapel responded that the Weibull based for 5%tile did not matter as they also tried different approaches.
R Harris commented on the representativeness of the sample with respect to the location etc. Ks should be location dependent. P Stapel agreed and stated that this would be especially problematic for tropical hardwood where the source of the material might not be known and producers wanted to reduce testing costs.

Influence of sample size on assigned characteristic strength values

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Abstract

According to EN 384, characteristic values for strength need to be adjusted for sample size and number of samples. The minimum sample number is 1 and the minimum sample size allowed is 40. With decreasing number of samples the statistical punishment factor (k_s-factor) reaches a minimum value of 0.78. It means that for a single grade and species, 40 specimens may be sufficient in order to determine characteristic strength values to be used with Eurocode 5. This minimum of 40 specimens is independent of the size of the growth area, generally considered as being one country. Since the introduction of EN 384, a large number of wood species and grades have been assigned to strength classes, varying from softwoods (mainly spruce and pine), low and medium dense European hardwoods like poplar, ash and maple to heavy tropical hardwoods such as cumaru und massaranduba. In this paper, a statistical analysis has been made for a number of species for which data is available. The influence of the sample size on the derived characteristic values is studied together with an analysis of the variation in (characteristic) strength values between subsamples. It is shown that EN 384 can be too liberal. The derived characteristic strength values of species, subsamples and grades are studied using the ranking method and 2-parameter weibull distributions. A proposal for an improvement in the current procedure to determine characteristic strength values on the basis of small samples is made.

1 Introduction

In the assignment procedure of grades to strength classes it is required that the sampling is representative for the structural timber that is brought onto the market. This would require comprehensive testing programmes to determine the characteristic values, as well as a continuous monitoring testing programme to discover possible deviations from the original assumption of being representative. In practice it is hardly possible to determine whether this is actually the case, as strength values assigned to certain grades are often based on few samples. Even with as few as 40 test pieces large areas can be covered.

In this paper the influence of the sample size and the growth area for which the sampling should be representative is discussed for both softwoods and hardwoods for visual and machine grading. This paper focuses on the assigned bending strength.

2 Requirements according to EN 384 and backgrounds

2.1 Requirements according to EN 384

According to its scope, EN 384 "gives a method for determining characteristic values of mechanical properties and density, for defined populations of visual and/or mechanical strength grades of sawn timber". This allows assigning grades and species to strength classes according to EN 338.

The following aspects need to be considered for the sampling:

- The sampling should be representative for production.
- Any suspected difference in strength should be incorporated in the sampling by taking different subsamples where these suspected differences are incorporated.
- The minimum amount of pieces in a visual grade is 40 pieces. A sample is defined as a number of specimens of one cross section size and from one population.

The characteristic value for the species and the grade has to be calculated as follows:

- For every subsample the 5%-percentile of the visual grade should be determined by ranking (non-parametric method)
- The characteristic value of the visual grade of the whole sample should be determined by calculating the weighted average 5%-percentile value of the subsamples. The weight is determined by the number of pieces in a subsample.
- The determined characteristic value should be multiplied by a factor k_s, which depends on the number of samples and the number of pieces in the smallest sample.
- The determined characteristic value should not be greater than the lowest 5^{th} percentile of the individual subsamples multiplied by 1.2.

Some consequences from the method described above are:

- The characteristic value of the grade is a weighted average value for the whole growth area.
- When timber from the entire growth area is not mixed during production, but is produced from regions represented by the subsamples, this timber may have an expected characteristic value of 1.0/1.2 = 83% of the assigned strength value for the case that k_s=1.0.

2.2 Background

The background for the k_s factor can be found in Fewell and Glos (1988). To bring into account the variability between the 5^{th} percentile values of subsamples 20 subsamples of 100, 200 and 300 pieces were randomly selected from a parent sample of 652 pieces of European redwood/whitewood. This result is shown in figure 1. This figure was adopted and modified to the k_s factor that is at present incorporated in EN 384 and shown in figure 2. Figure 2 is a result of a statistical exercise on a parent sample of European redwood/whitewood, but has not been verified on any actual sample analysis with test data or on any other wood species with possible different characteristics.

EN 384 requires that sampling is representative for the whole population. Proof of representativeness is however difficult to achieve. A number of parameters influence the population characteristics (a.o. growth area, climate conditions, forestry practices, sawmill operations) but it is virtually impossible to cover these influences in a test programme to determine engineering values for timber. From EN 384, it can be read that a minimum of 40 specimens is enough, but with the consequence of a statistical punishment (k_s-factor of

0.78). This is done to account for the uncertainty in characteristic strength values caused by the small sample size. In the following, an analysis on the k_s is performed, using a number of different wood species covering EN 338 strength classes from C 24 to D 70. It might be a coincidence, but the minimum ratio in figure 1 for a subsample of 100 beams is around 0.78, exactly the same as the minimum k_s factor in EN 384 for a single subsample with the minimum required 40 specimens.

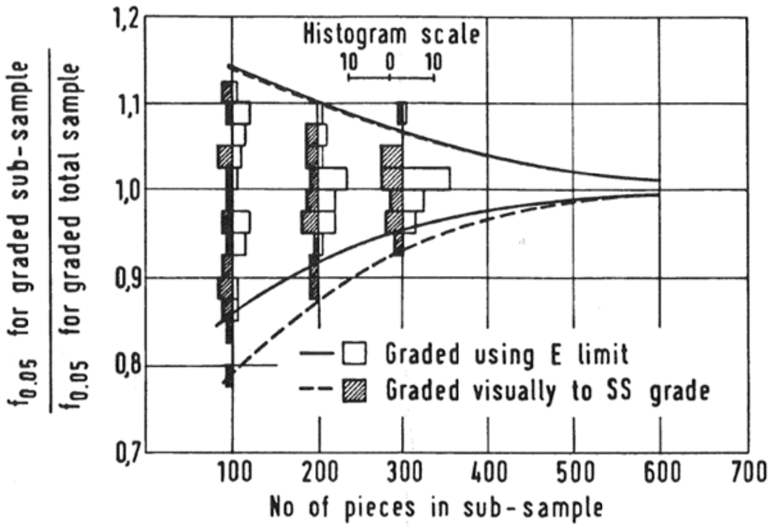

Figure 1: Ratios of lower 5% bending strength values of randomly selected sub-samples from a parent sample of 652 pieces. Taken from Fewell and Glos (1988).

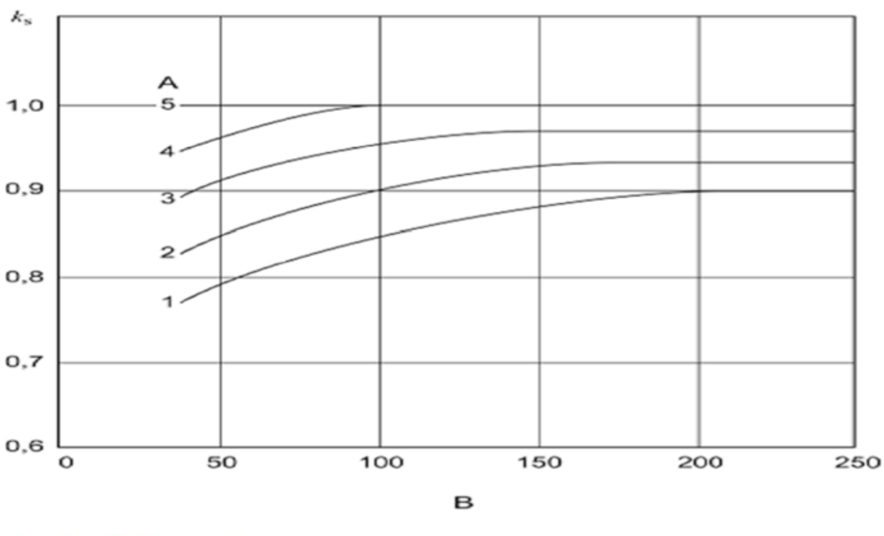

Figure 2: Required k_s-factor depending on the number of samples and sample size according to EN 384.

3 Materials and Methods

3.1 Materials

Bending test data is available for European soft- and hardwoods, as well as for tropical hardwoods from South-America. The data is separated with respect to origin and sample size. Depending on the available non-destructive test data used for grading the timber, datasets are used for analysing the results of visual grading, machine grading or both.

European Softwood

For machine grading 4893 datasets of Norway spruce (*Picea abies*) from Europe are analysed. The data covers many parts of Central, North and Eastern Europe. The sampling was carried out in different regions within 11 different countries. The cross section also covers a broad range: the thickness varies from 20 to 167 mm and the width (depth) from 63 to 284 mm. A more detailed description of the samples was given by Stapel et al. (2010). Separating the dataset according to EN 384 requirements leads to 53 samples. The minimum number of pieces in one subsample was 20, the maximum 518. For machine grading it is not mandatory to separate samples for cross-sections. As EN 384 requires this, 4 subsamples with less than 40 pieces are formed.
Less visual grading data is available. In addition to 1547 specimens of Norway spruce, 391 specimens of Scots pine (*Pinus sylvestris*) and 157 specimens of Douglas fir (*Pseudotsuga menziesii*) are available. Norway spruce was sampled in Central Europe, Scots pine and Douglas fir originated from German forest stands. The thickness varies from 20 mm to 165 mm and the width (depth) from 70 mm to 252 mm.

European Hardwood

Three European hardwood species are included in the analysis: European ash (*Fraxinus excelsior*), Sycamore Maple (*Acer pseudoplatanus*) and black poplar (*Populus nigra*) 1250 specimens from different stands within Germany were analysed. Compared to the softwood species, the range of the cross-sections was small. All pieces had a thickness of 50 mm and widths between 100 mm and 175 mm.

Tropical Hardwood

Two tropical hardwoods are analysed: cumaru (*Dypterix spp.*) and massaranduba (*Manilkara spp.*). For cumaru and massaranduba the trade name represents a genus with more species, indicated by the extension spp. Since some wood species are distributed over a whole continent, the source area of the samples is not always clear. As a result the samples can represent a small or huge growth area. The cumaru samples originate from Brazil, Peru and Bolivia, while massaranduba was sampled only within Brazil. Tested width for massaranduba was between 100 mm and 150 mm, for cumaru between 100 mm and 170 mm. Thickness for both species was between 40 mm and 64 mm. Only graded material was available.

Testing of the Material

All destructive tests were performed according to EN 408. The factors given in EN 384 (k_h-factor, k_l-factor) were applied. A symmetrical two point loading was used for the determination of bending strength, usually over a span of 18 times the depth. If possible the weakest section along the beam axis was tested. For tropical hardwoods the weak zone is mostly not visually recognizable. This means that the weakest zone is randomly present over the specimen length. The orientation of the board in edgewise bending tests was chosen randomly.

Table 1 summarizes the available data and gives basic statistical values for the tested species.

Table 1: Number of pieces, number of samples and bending strength values for tested species.

Species	n	no of subsamples	bending strength	
			mean	cov
European Softwood				
spruce	1547	14	39.3	30.6
douglas	157	2	49.4	35.0
pine	391	4	37.6	34.5
machine graded spruce	4893	53	40.6	32.4
European Hardwood				
maple	459	4	56.6	33.4
ash	324	4	69.8	23.1
poplar	467	5	44.5	33.0
Tropical Hardwood				
massaranduba	146	3	99.4	31.6
cumaru	223	5	106.8	25.0

3.2 Methods

For the analysis all specimens are graded either visually or by machine.

Based on the 4893 datasets for which laboratory data for density, eigenfrequency and knot value are available Stapel et al. 2010 calculated a model by means of (multiple) linear regression analysis. This model reflects real machine strength grading and is used here. The settings were derived for a so called "machine controlled system" in compliance with the current standard EN 14081. Single countries are used as subsamples on which the derivation of settings is based. The resulting settings would be valid for large parts of Europe.
Settings for a low grade (C 24) and a high grade (C 35) were used to check the effects for machine strength grading. The grades were not analysed in strength class combinations.

DIN 4074-2 was used to grade European softwood species for which the necessary visual data was recorded. DIN 4074-5 was used for hardwoods. Each standard gives the same eleven features which need to be considered for the assignment into a visual strength class. However limit values differ depending on the species. For the grading we focused only on the following three major criteria: knot size, existence of pith, year ring width. Depending on its properties, a board can be assigned to the visual strength class 7, 10 or 13. The higher the number is, the higher is the expected strength values. Softwoods get the prefix S, Hardwoods LS.
The visual strength class 7 was not analyzed. Both of the higher strength classes were analysed separately. Additionally, boards graded into the visual strength classes 10 and 13 were analysed combined in a so called strength class "10 and better" (L 10+ / LS 10+).

Visual strength grading of dense tropical hardwoods is generally restricted to slope of grain and some limit on growth defects such as knots or other growth disturbances that may be present in hardwoods. In most cases, such as NEN 5493 and BS 5756, the growth defect size is limited to 0.2 times the size of the face on which the defect is visible. Slope of grain has a typical limit of 1:10, but when sampling is done timber with exactly these defects are often difficult to find. Consequently, the limits present in the standards are also meant to prevent too big defects coming onto the market for which no test data is available, without reducing the strength to an unsafe level. For ring width generally no requirement is given.
The two tropical hardwood samples were graded into grade C3 STH according to

NEN 5493, which is equal to BS 5756, except for a minor difference in slope of grain which is 1:10 for NEN 5493 and 1:11 for BS 5756.

Bending strength values were determined, if 40 or more pieces were graded into the same grade. For the 5^{th} percentile characteristic value this was done by ranking and by a two parameter Weibull distribution using SPSS software. Multiplying the 5^{th} percentile characteristic value determined by ranking with the k_s-value for the subsample leads to the characteristic strength value which would have been assigned to the species if only this sample had been tested. Depending on the number of specimens in this subsample, the used k_s-factor in the analysis varies between 0.78 and 0.9.

In addition, all samples of each species were analysed together. The 5^{th} percentile characteristic value was determined by calculating the weighted mean of the 5^{th} percentile characteristic value of each sample. The values were weighted by the number of pieces in each sample. Additionally, the lowest of all 5^{th} percentile characteristic sample values was multiplied by 1.2 according to EN 384. This results in two 5^{th} percentile characteristic values. The lower value was chosen and multiplied by a k_s-factor for the species, resulting in the ´real´ characteristic value. Depending on the number of specimens and the number of samples available for the species and grade, the used k_s-factor can vary between 0.78 and 1.0.

Then, for each subsample, the ratio between the characteristic value of the sample and the ´real´ value was determined. In principle, the characteristic 5^{th} percentile value of the subsample, multiplied with k_s should lead to a safe design value, i.e. a value equal to or higher than the ´real´ characteristic value. If ratios higher than 1.0 are found for subsamples, the current method in EN 384 is on the unsafe side, assuming that the ´real´ characteristic value is accurate. The following equation summarizes the procedure mathematically.

$$Ratio = \frac{k_{s,i}\, f_{m,0.05,i}}{k_{s,j} \cdot \min\left(1.2\, f_{m,0.05,i,\min}, \frac{\sum_{i=1}^{j} n_i\, f_{m,0.05,i}}{\sum n}\right)} \qquad (1)$$

in which:

$f_{m,0.05,i}$	= 5-th percentile bending strength of subsample *i*
$f_{m,0.05,i,\min}$	= lowest 5-th percentile bending strength of *i* – subsamples
j	= the number of subsamples
n_i	= the number of specimens in subsample *i*
n	= the total number of specimens
$k_{s,i}$	= factor taking into account the size of subsample *i*
$k_{s,j}$	= factor taking into account the number of specimens in the smallest subsample *i* and total number of subsamples *j* (for $j \geq 5$, $k_{s,j} = 1$)

4 Results

The grading results for the single species are given in Table 2. The separation into different cross-sections and origins had the effect that less than 40 pieces are found for certain species and grades. For European softwoods not enough pieces were available in the visual strength class S 13. For Douglas fir, the total number of pieces was too low to have separate results neither for S 10 nor for S 13. For European hardwoods the share of timber in class LS 10 was too low.

Table 2: Grading results for different species and grades.

grade	species	n	mean	cov	f_0,05_weibull	f_0,05_rank	$k_{s,j}$	f_EN_384
S 10	pine	185	39.9	27.9	21.9	22.7	0.90	18.7
S 10	spruce	832	42.7	26.0	24.2	23.6	1.00	22.6
S 10 +	douglas	96	56.4	28.4	29.3	27.4	0.83	24.7
S 10 +	pine	246	42.4	29.2	22.7	23.6	0.96	22.0
S 10 +	spruce	969	43.3	26.2	24.5	24.3	1.00	22.7
LS 10 +	maple	311	59.6	30.8	28.6	30.0	0.97	28.6
LS 10 +	poplar	317	49.4	27.1	26.1	26.9	1.00	20.6
LS 10 +	ash	257	72.2	20.8	45.7	44.9	0.96	37.0
LS 13	ash	207	75.3	18.1	51.1	52.8	0.95	46.9
LS 13	poplar	216	54.1	20.8	34.7	36.4	0.90	31.2
LS 13	maple	242	62.8	28.2	31.4	32.3	0.95	28.0
C 24	spruce	4773	41.1	31.3	20.4	21.4	1.00	16.1
C 35	spruce	1391	53.2	20.0	34.8	35.1	1.00	33.9
C3 STH	massaranduba	146	99.4	31.6	47.0	51.0	0.89	43.8
C3 STH	cumaru	223	106.8	25.0	59.7	56.8	1.00	56.3

The lowest $k_{s,j}$-factor on the complete species is used on douglas fir, as only two samples were available from the beginning. For several grades $k_{s,j}$ = 1.0 as at least five samples are present for the grade. Only for S 10+ for douglas fir and pine and for S 10 for pine, the weighted mean of the 5th percentile strength values was used to get the characteristic strength value according to EN 384. In all other cases this value can be explained by one weak sample. In most cases the difference between the minimum value and the weighted mean is less than 5 N/mm². Differences are bigger for machine graded C 24 and tropical hardwoods. The extreme is reached for massaranduba, showing a difference between both values of 17.7 N/mm².

5th percentile values determined by ranking method are close to the results for 5th percentile values based on weibull distributions. As this can even be found on the basis of the single subsamples, no distinction between the two is made in the following analysis and only the ranking results are used.

Figure 3 shows the ratio for the EN 384 value which would have been calculated for single subsamples and the value which would result determining the expected strength value for all samples - also based on EN 384. The results are shown separated by countries, for which a country code is given on the x-axis. As there are 42 subsamples with more than 40 pieces in a grade it is obvious, that the subsample with the lowest 5th percentile value is responsible for the ´real´ characteristic value. This value resulting from one subsample has a 5th percentile characteristic value as low as 13.4 N/mm². This results in a reference value of 16.1 N/mm², while the value for the weighted mean is 22.1 N/mm². According to

EN 14081-2 the required characteristic strength for C 24 is 21.4 N/mm². This value is indicated by the red dotted line.
The results for C 35 are also shown in Figure 3. The dots indicate the ratio. For countries with low quality timber or small sample sizes it is not possible to grade at least 40 pieces into C 35. Only the ratio value for one sample lies slightly above 1.0. This is the case even though the reference value again depends on one single subsample. Compared to C 24 the difference between the value based on the one SI sample (33.9 N/mm²) is much closer to the value for the weighted mean (36.1 N/mm²).

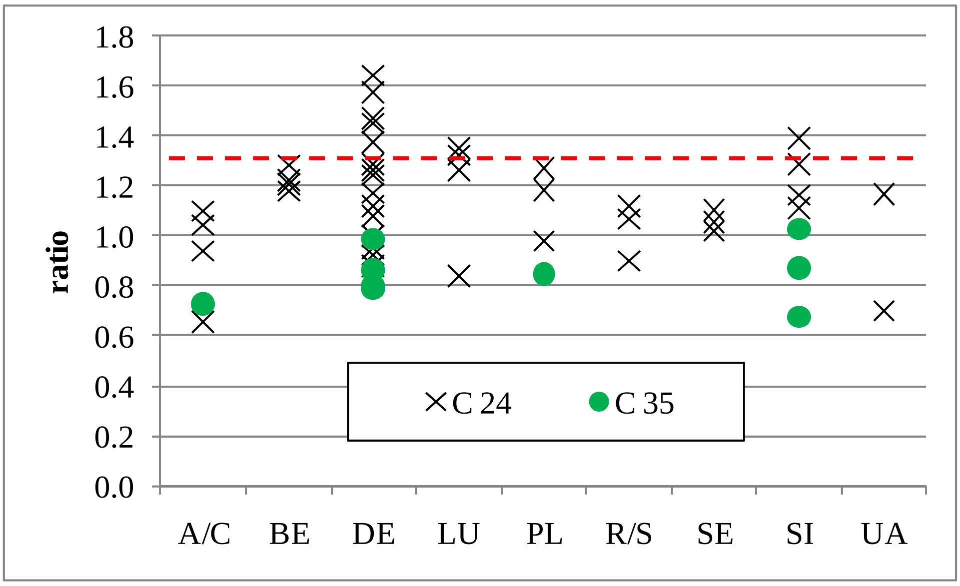

Figure 3: Ratio for machine graded timber in grade C 24 and in grade C 35 separated for countries. The red dotted line indicates the required characteristic strength for C 24 according to EN 14081-2.

Visual grading results are shown in Figure 4. Results for 33 subsamples are available in S 10+ for softwoods and LS 10+ for European hardwoods. The highest characteristic strength difference can be found for poplar: The sample with the lowest strength reaches a characteristic value of 17.2 N/mm², while the highest one reaches a value of 30.4 N /mm².
When the visual grades are more specific and grading is done to visual classes 10 and 13 separately subsamples become smaller and k_s-factors decrease for subsamples. For one subsample of maple this still leads to a recognizable high ratio, as the decrease of the characteristic strength of this sample from 48.1 N/mm² to 37.5 N/mm² is not big enough. For softwoods graded into S 10 most ratio values are below 1.0 with few values being slightly higher than 1.0.
For tropical hardwoods the situation is quite different. For both species the 5th percentile strength values of the different samples show a large scatter. For cumaru the values range from 47.0 N/mm² to 100.9 N/mm², for massaranduba from 41.1 N/mm² to 86.2 N/mm².

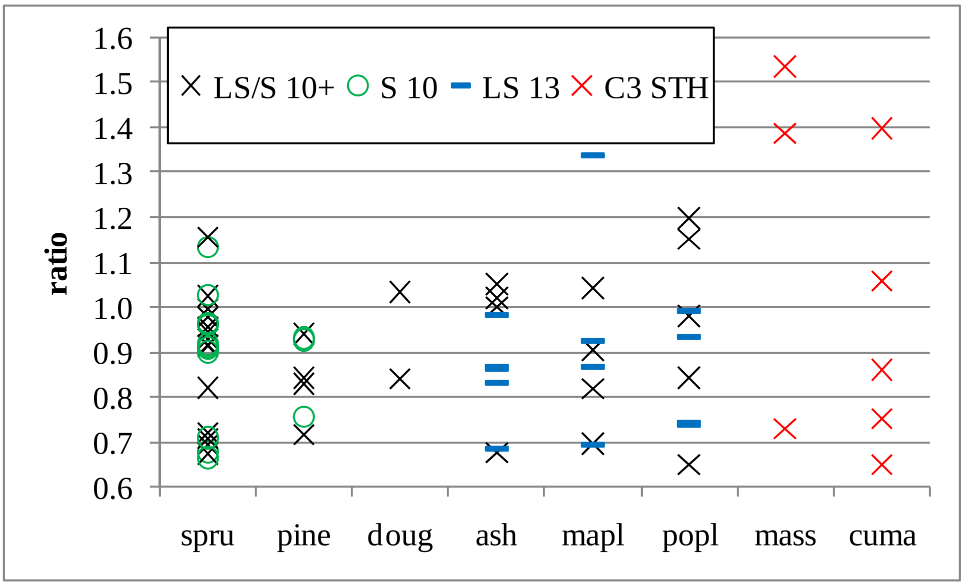

Figure 4: Ratio for visual graded timber in grades S 10+, LS 10+, S 10, LS 13 (according to DIN 4074-1 & DIN 4074-5) and C3 STH (according to NEN 5493).

In Figure 5 the ratios given in Figure 3 are Figure 4 are used, but now plotted over the number of pieces per subsample. For better visualization only sample sizes below 200 pieces are shown. For the machine grade C 24 there are 6 samples with more specimens. The biggest sample has 516 specimens with a maximum ratio of 1.29, which is still considered high.

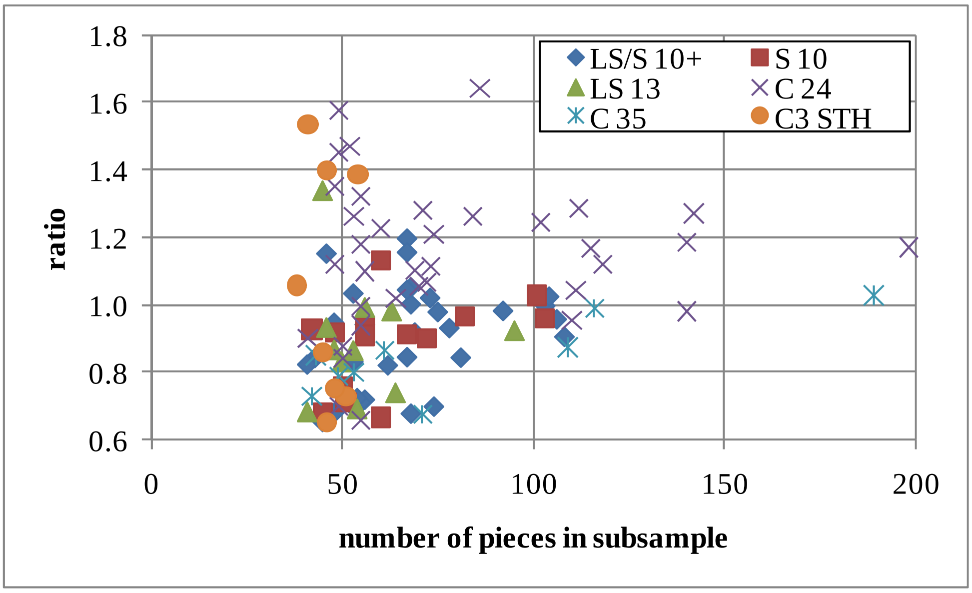

Figure 5: Ratio of single samples compared to the number of specimens in each grade - for sample sizes below 200 pieces.

In Figure 6, the ratio of Fewell and Glos is presented, where the ratio between the ranked 5^{th}-percentile of the individual sample (without $k_{s,i}$) and the ranked 5^{th} percentile of the whole sample (without $k_{s,j}$) is used. This Figure can directly be compared to Figure 1, but now subsamples smaller than 100 specimens are included, showing a considerable increase in the ratio.

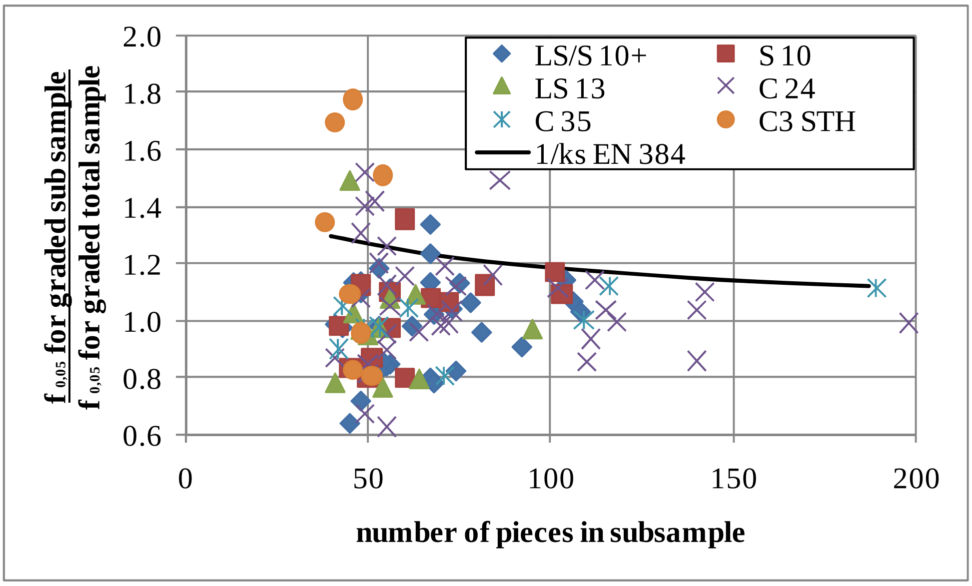

Figure 6: Ratio used by Fewell and Glos (1988). k_s-line according to EN 384.

The coefficient of variation for the individual subsamples, plotted in Figure 7 also seems to have an influence on the calculated ratio. Machine graded C 24 (and better) shows similar COV´s per subsample as visually graded timber, but with much higher ratios.

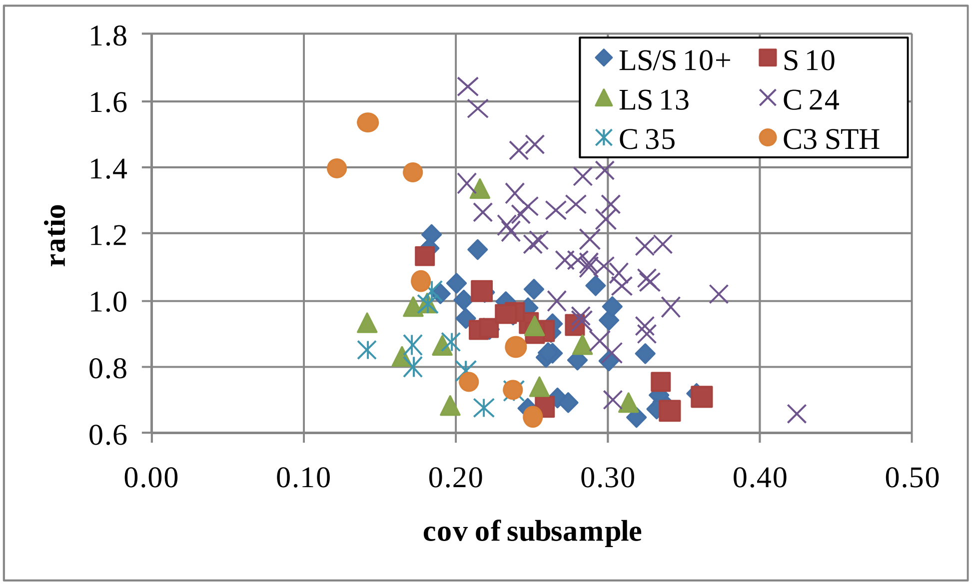

Figure 7: Characteristic value ratio as a function of the coefficient of variation in subsamples.

5 Discussion

In 49 out of 117 cases the value of the ratio between a single sample and the full sample is higher than 1.0. If characteristic values would have been derived on the basis of this sample instead of on all available data for the species, the assigned characteristic strength value would have been higher than the declared value. This is the case even though the k_s-factor, which should prevent this effect, has been applied in the derivation. Consequently the $k_{s,i}$-factor according to EN 384 is too small.

The effect can be small or in practice not recognizable at all, depending on the absolute 5th percentile strength value. However, for species in high strength classes and small COV´s in the subsamples, the effect can be considerable. The highest 5th percentile strength value of

all samples was reached for a cumaru sample from Brazil (100.9 N/mm²). Based on all five samples, cumaru would be assigned to D 50, while using a minimum k_s-factor of 0,78 on the maximum value would have allowed for an assignment in D 70. (D 55 and D 75 would be possible, if these classes existed).
Grading quality has a big influence on the assignment of a strength class. This is especially true if many samples are available. In this case strength values can become very low, which can be seen for C 24. As samples are separated due to source and cross-section, single values of small samples are responsible for the overall assigned characteristic value. That is one reason for the high ratio values of C 24. If the characteristic strength values of the sub-samples multiplied by the corresponding k_s-factor were compared to the required strength value for machine graded C 24 (21.4 N/mm²) the maximum ratio would be 1.23.

A tendency for a smaller COV for tropical hardwood subsamples can be noticed, at the same time observing high ratios for subsamples with low COV´s. As a consequence, the smaller the COV of subsamples, the more subsamples should be taken in order to cover the variety in the timber production for the large growth areas of tropical hardwoods. For European data this effect seems however much less present.

6 Conclusions

Sample size and number of samples have a significant influence on the characteristic strength values which are assigned to certain species and grades.
Assigning strength class to certain grade and species based only on 40 pieces is unsafe using the current rules. Especially if assignments are made for complete continents, as is currently the case in EN 1912.
Clearly, from Figure 3 to 6 it can be concluded that the value of k_s for a single subsample with up to around 100 specimens is on the unsafe side. The value of k_s should be lowered to around 0.5 for a subsample size of 40 specimens and to around 0.8 for a single subsample with around 100 specimens. Based on the ratio between the characteristic strength value of the subsamples and the strength value for the total sample calculated according EN 384, a proposal for a new line is given in Figure 8. It is expected that curves for more than 1 subsample need to be adjusted accordingly. The subdivision of subsamples is different for EN 384 and EN 14081-2. As a consequence the suggested line can only be applied for visual grades.

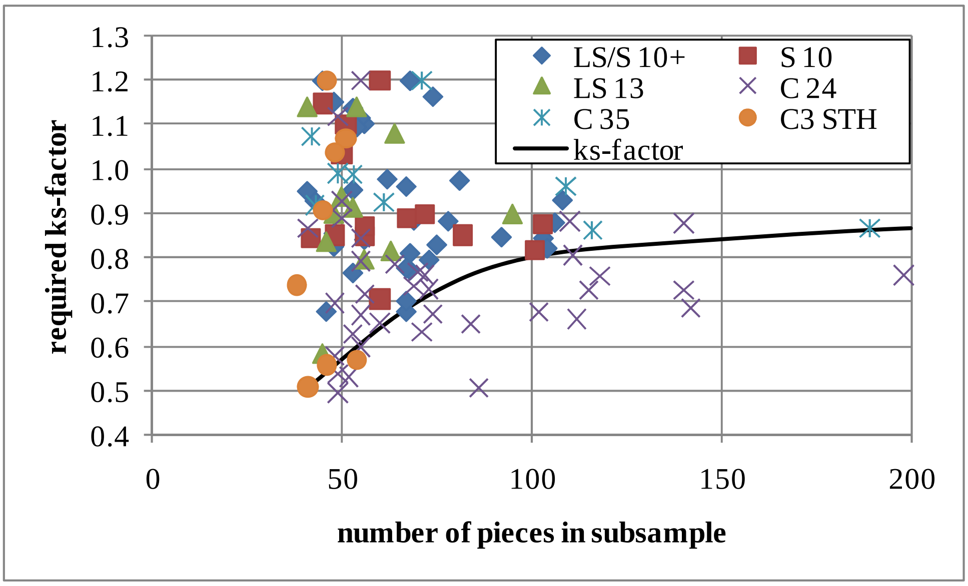

Figure 8: Suggestion for the EN 384 k_s-factor for 1 subsample.

7 References

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IV

Analysis of determination methods for characteristic timber properties as related to growth area and grade yield

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Abstract

The origin of the raw material is a key aspect for strength grading of timber. Large grading areas are favoured by the sawmilling industry as they require less effort in handling and documentation during the production process. However, large growth areas can also cause problems, as too high mechanical properties can be declared or yields may become uneconomical.

The presented study presents a method that should allow for timber from different countries to be combined into a single grading area. Additionally, the influence on the yield for guaranteeing timber properties for differently defined populations is analysed. In this process, a number of available calculation methods for characteristic values for MOR, MOE and density are considered as the determination method also influences the final yield. Non-destructive and destructive test data from 8487 spruce specimens from Europe tested in bending or tension is the basis for the presented study.

Based on the grading results the presented method is able to simply identify countries that may be combined. The definition of pan-European grading areas seems problematic if characteristic timber properties need to be guaranteed separately for each individual country as it may result in a severe drop in yield. However, checking timber properties only for the European population is unsatisfying as calculated timber properties considerably vary depending on the origin. As for the calculation method, the preferred method itself seems to have less impact on bending class assignments then on tension class assignments.

Keywords: characteristic values, grading standard, machine grading, mechanical properties, sawn timber, strength grading

Introduction

The interest in machine strength grading in Europe is increasing. Machines have to be evaluated according to EN 14081-2. This procedure is complicated as discussed by Bengtsson and Fonselius (2003) and Ziethén and Bengtsson (2011). Despite an increasing number of available machines on the market, there are still some severe barriers for grading machines.

Problems related to the origin of the timber to be graded are among the most important (Ranta-Maunus et al, 2011) as the origin of the timber usually comprises several parameters - such as genetics, nature of soil, weather conditions or silviculture (Glos, 1978) - that influence timber properties. In this context, it is of interest from which origins timber is graded together. The combination is called grading area. To define large grading areas is not easy as timber properties usually have to be guaranteed for all origins. More origins usually go along with increased variations of timber properties and result in higher settings and lower yields. Thus, deriving grading machine settings that produce both safe and economic building material is a challenge. The costs in terms of yield for guaranteeing timber properties for different sized grading areas (Europe, regions, countries) has so far only been superficially analyzed (Denzler and Stapel, 2011). If it is desirable to guarantee timber properties separately for each country with only one setting boundary valid for all countries within the grading area, the settings have to be conservative in order to reach the strength, stiffness and density requirements. However, this leads to an inefficient use of the raw material.

Therefore, this paper deals with the following questions:

- Timber from *which countries can be graded together*? What information is needed to show that equal settings work for several countries and a grading area can be formed?
- What are the *costs for guaranteeing timber properties* on European, regional (Central Europe/ Eastern Europe) or country level?

These questions are directly connected with the basics used to derive characteristic values for MOR, MOE and density. For the derivation of machine settings a lot of destructive tests are required. The procedure currently requires that timber from each single country has to be tested in order to get the grading machine approved for the grading area. As a minimum requirement testing of 100 pieces per origin is defined in the corresponding standard EN 14081-2. The used calculation routine for MOR, MOE and density in Europe today is based on a non-parametric approach which requires at least 20 pieces in each grade (EN 384). If only a few pieces are available for an origin in a grade the derivation of reliable settings is difficult. This is especially true if settings for very high strength classes, very low strength classes, or combinations with at least three strength classes are derived. Usually, only a limited share of the total sample can be assigned to these classes. In order to overcome this problem, a proposed new procedure shall no longer require a calculation using the non-parametric “ranking method” but should reference prEN 14358. In this standard, normal or log-normal distributions for timber properties are assumed. The standard allows the assignment of timber properties on as few as 2 pieces per grade.

Until today, parametric as well as non-parametric approaches are available and applied. In the case of MOR the fit of the normal distribution is questioned, especially on the level of the 5^{th} percentile value. Therefore, in most cases a lognormal distribution or a non-parametric approach is used to predict MOR on the level of 5^{th}. Weibull distributions (2 or 3 parameter) often shows equivalent or even more stable results compared to the non-parametric values but especially the 3-parameter Weibull distribution is not easy to handle in practice based on the author's knowledge. For density, a test on normal distribution often is statistically acceptable. Using a normal distribution to calculate the 5^{th} percentile density often leads to lower density values than using a non-parametric approach (e.g. Daniel Ridley-Ellis, 2013).

The non-parametric approach can easily be adapted to the data but can lead to unstable results especially for a small number of specimens. If it comes to graded material, the property distributions are cut at least at one end. This leads to mathematical approaches having difficulties in representing the data properly. This clearly shows that the calculation for the “true” characteristic value cannot be defined. Hence, different calculation options are often considered in research papers (Glos 1983, Fewell and Glos 1988). With increasing sample sizes, methods deliver comparable results. Rouger (2004) analysed the methods given in a number of standards and suggests abandoning the non-parametric approach as applied in EN 384.

This directly leads to the third question analysed in this paper:

- What are the differences between the *calculation methods* for characteristic values? How does a possible change in the standard procedure influence the settings?

As this question forms the basis for answering the other two, the paper will discuss the last question first. How good the method actually determines the 5^{th} percentile values in relation to the actual test data is not part of this paper.

Materials and Methods

Material

Norway spruce (*Picea Abies*) from Central, Eastern and Northern Europe is used for the analysis. A share of fir (*Abies alba*) is included in the sample, as the two species are processed together. Only sawfalling material is used. The sampled timber was tested at eight European research institutes in the course of the Gradewood Project. Round robin tests were carried out before the actual laboratory measurements at the different institutes to ensure reliable and comparable destructive and non-destructive test data. Data from recent projects at Holzforschung München is also considered. In total, 8487 specimens were tested, almost divided equally in bending or tension tests. The data is analysed separately for these two loading modes.

Testing of the material

Prior to destructive testing the dynamic modulus of elasticity at 12% moisture content was determined using the eigenfrequency, the density and the length for all specimens as well as its moisture content for correction. The destructive tests have been performed according to EN 408 and the factors given in EN 384 (k_h-factor, k_l-factor) have been used to adjust the single measurements to standard conditions. Whenever possible, the weakest section along the beam axis was placed between the loading points. The orientation of the board in edgewise bending tests was chosen randomly. Test values for the static bending modulus of elasticity not tested at the reference conditions were adjusted to 12 % moisture content by 1 % for each percentage difference in moisture content. Table 1 gives a short overview of the test values reached in bending and tension. Values for the three grade determining properties are given for the complete dataset (Europe). Specimens tested in bending originated from AT, CZ, DE, SK, FR, SE, PL, RO, SI, UA, BE, specimens tested in tension from CH, PL, LV, AT, CZ, SE, UN (unknown but within CE), SI, RO, DE, SK, UA. Values are given separately for samples taken from this dataset – Central Europe (AT, BE, CZ, DE, UN) and Eastern Europe (RO, SK, UA). The dataset is divided into smaller units, usually on the basis of the country of origin, which are also considered for grading exercises that are specified below. Timber from 11 countries is available for analyzing bending strength class and class assignments. For tension strength, timber from 12 countries is available.

Table 1: Strength, stiffness and density mean values and coefficients of variation for ungraded spruce. Values calculated according to EN 384 for Europe and separated for Central and Eastern Europe.

Testingmode	Origin	n	MOR		MOE		density	
			Mean	cov	Mean	cov	Mean	cov
			MPa	%	MPa	-	kg/m³	-
Bending	Europe	4331	39.5	33	11300	26	432	12
	Central	1475	37.9	33	11200	26	437	12
	Eastern	840	35.7	31	10000	24	396	10
Tension	Europe	4156	28.6	41	11200	23	435	12
	Central	2230	30.1	39	11500	23	449	11
	Eastern	844	26.2	42	10300	21	395	10

The tension data sample from Switzerland (CH) features special testing conditions especially emphasized for analysis on country level. It was tested over a span longer than 9 times the height of the board. For tension tests no factor for the adjustment of the length is given in EN 384. With increasing spans the possibility of covering a weak section increases as length effect in timber exist (Barrett et al 1995). Thus, the timber from CH is expected to show lower strength values compared to other timber from CH that is tested over the minimum required span. The timber is used for the analysis as it might represent a weak sample and is included in the European dataset but not in the Central European sample. The presented method here is expected to identify this sample.

Methods

Machine grading can be based on a number of parameters. In the present work only the dynamic modulus of elasticity is used as the predictor variable for the timber properties. Laboratory measurements that are equivalent to real machine values were used. The modulus of elasticity is known to be a good single predictor (or indicating property = IP) for timber strength.

For some comparisons a basic separation of the dataset into different strength class combinations is necessary. This separation requires the derivation of settings which is done using the IP based on the modulus of elasticity. The setting derivation is based complete bending or tension data. Characteristic values are usually determined according to EN 384 in this step. Detailed information is given when necessary for the three different aspects: *Methods for the calculation of characteristic values, Countries graded together, Costs for guaranteeing timber properties.*

The procedure of EN 14081-2 was not strictly followed as this part requires a lot of interpretation and is not influencing the results of this study. Essential factors, like the 0.95

factor for MOE and the k_v-factor for strength were used. If settings are derived in a different way, it is explained where applicable.

Methods for the calculation of characteristic values

Table 2 summarizes the analysed calculation methods.

Table 2: Calculation of characteristic values according to EN 384 and prEN 14358. The calculation methods to be used for the parts “methods for the calculation of characteristic values” and “costs for guaranteeing timber properties” are printed in bold.

	MOR 5th percentile [MPa]	MOE mean [MPa]	density 5th percentile [kg/m³]
EN384	**n>= 40 non-parametric without considering sample size**	**n>= 40 non-parametric without considering sample size**	**n>= 40 non-parametric without considering sample size**
prEN14358_lognormal	**n>= 2 parametric (lognormal) considering sample size**		n>= 2 parametric (lognormal) considering sample size
prEN14358_normal	n>= 2 parametric (normal) considering sample size	**n>= 2 non-parametric considering sample size**	**n>= 2 parametric (normal) considering sample size**
prEN14358_ranking	n>= 40 non-parametric without considering sample size		n>= 40 non-parametric without considering sample size

According to EN 384 a non-parametric approach is required for the calculation of the strength and the density 5th percentiles which can cause problems if only few data are available. For this reason, an analysis is performed to check whether other assumptions and calculation methods are a valid alternative. What are the differences between the currently used method given in the valid version of EN 384 (EN 384) and the proposed method (prEN 14358)? Certainly, differences have to be expected also for large datasets as in the prEN 14358-method a log-normal distribution is proposed for strength values and a normal distribution for density values. This might cause problems especially for graded timber. Besides, for strength values the possibility of calculating 5th percentiles based on a normal distribution is possible if the sample shows the respective distribution. Also ranking is possible if a certain amount of pieces are available. Alternatives are also given for density values. For the modulus of elasticity the mean value is of importance. However, small differences have to be expected also in this case as additional factors have to be considered for all properties following prEN 14358. These factors are supposed to take into account the sample size used for the calculation. Small sample sizes lead to a reduction of all characteristic values independent of the assumed distribution if prEN 14358 is applied.

These calculation methods are compared on the basis of the complete datasets. The strength class combinations for bending strength class combination C35-C24-rej and for tension class combination L36-L25-L17-rej are used. For both class combinations the settings for the single classes are based on the characteristic values calculated according to EN 384. However, the exact setting value is of minor importance for the comparison of the calculation methods. In each grade the settings are gradually raised in steps of 100 (IP) to check the developing of characteristic values for changing settings. Difference in characteristic values can be analysed for different setting values for each grade.

Countries graded together

While the calculation method might influence the final settings, it is only of secondary importance for comparing timber properties from different countries. For the presented result only EN 384 method will be used. The method can be adopted to fit any other proposed calculation method. The purpose of this exercise is to find out which countries can be safely graded together (using shared settings) and which countries cannot.

Comparing grading results without testing several grade combinations would simplify the process of setting derivation. Here, a stepwise approach was chosen. For each step, grading results for one IP value were analyzed. Also in this case, the IP was raised in steps of 100. As only pieces above the setting are analysed, fewer pieces become available after each raise. For these kind of grading machines the settings usually range somewhere between 7000 and 16000 (EN 14081-4). The starting point at the lower end of IP values was set at 8000, as 8100 is the first value for which reject occurs in every country. A setting of 15300 was used on the upper end as for all countries at least two pieces were in-grade. Based on the in-grade timber characteristic values for MOR, MOE and density were calculated. This was done separately for each country (e.g. $MOR_{IP,country}$) as well as for the complete, European dataset (e.g. $MOR_{IP,EU}$). The difference between the value from a country and Europe is weighted by the percentage of the material per country fulfilling the required IP for the single steps. Figure 1 illustrates the basis of the calculation of the differences between the percentile MOR values between Europe and an individual country. Only values for which the characteristic value of the country is below the one for Europe are included, as these are considered a risk.

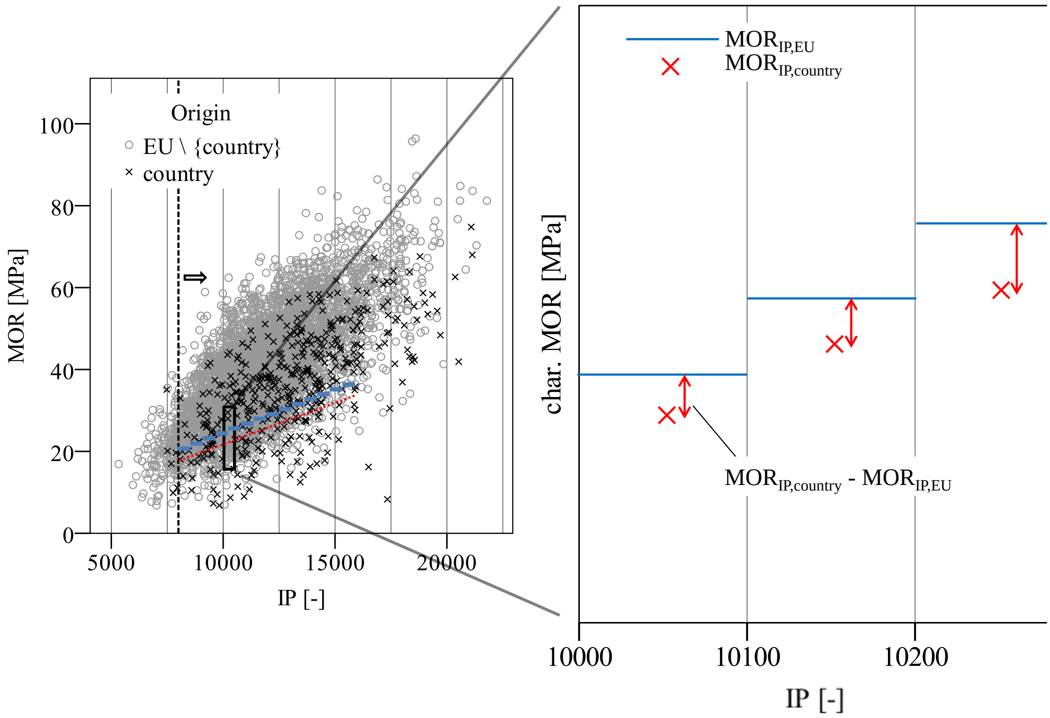

Figure 1: Illustration of the calculation of differences between European and country 5th percentile strength values.

Equation 1 shows how these absolute RISK values can be calculated for the example (MOR) shown in Figure 1. They express the deviation that has to be expected due to the fact that the settings have not been derived separately for single countries.

$$RISK\ MOR = \sum_{IP=8000}^{15300} MIN\left(MOR_{\mathrm{IP,country}} - MOR_{\mathrm{IP,EU}} | 0\right) \times \frac{n_{\mathrm{IP+100,country}} - n_{\mathrm{IP,country}}}{n_{\mathrm{ungraded,country}}} \quad (1)$$

where:

IP	Indicating Property / dynamic MOE
$MOR_{\mathrm{IP,country}}$	Characteristic strength for a country at IP value
$MOR_{\mathrm{IP,EU}}$	Characteristic strength for Europe at IP value
$n_{\mathrm{IP,country}}$	Number of in-grade specimens for a country at IP value
$n_{\mathrm{ungraded,country}}$	Total number of specimens for a country

While this equation allows assessing the risk of including single countries in a grading area in which jointly derived settings are used, information about the loss in terms of lower yields for certain countries is still missing. This information can be obtained by considering only differences in characteristics between countries and Europe for steps that show higher values for countries:

$$LOSS\ MOR = \sum_{IP=8000}^{15300} MAX\left(MOR_{\mathrm{IP,count}} - MOR_{\mathrm{IP,EU}} | 0\right) \times \frac{n_{\mathrm{IP+100,count}} - n_{\mathrm{IP,count}}}{n_{\mathrm{ungraded,count}}} \quad (2)$$

Values for MOE and density are calculated accordingly for the *RISK* and the *LOSS*.

In addition absolute *RISK* and *LOSS* values for all three properties are normalized by dividing them through the characteristic values for the ungraded European dataset. These values are referred to as *relative RISK and LOSS* values.

Costs for guaranteeing timber properties

While the approach above was independent of grades and grade combinations, the following part is closer to grading procedures in practice as different actual strength classes and strength class combinations are in the focus. Different calculation methods and regional zoom levels are analysed.

Both, the calculation methods given in EN 384 and the favored calculations for prEN 14358 (log-normal for strength, normal for density) will be considered when the *"Costs for guaranteeing timber properties"* are analyzed (Table 2).

Characteristic properties are calculated for both bending and tension data for three levels: 1. Europe (data from all available countries). 2. Central Europe and Eastern Europe. 3. Countries. Table 1 gives the mean values and the coefficients of variation of the grade determining properties for Europe, Central and Eastern Europe.

Here, several settings need to be calculated in such a way that grade requirements are met for different regional levels: whole Europe (complete dataset), a region (CE & EE) and for each country. If characteristic values are guaranteed on European level instead for each single country the settings have to be adjusted and therefore the yield will change. The comparison is based on the total dataset (Europe) using the yield as the indication variable.

The procedure of EN 14081-2 is not strictly followed. A setting is considered acceptable if the characteristic values are met. Today, mandatory checks (although not required in the standard) of characteristic values of single countries are usually accountable for an increase in settings. This approach was followed. In contrast to the requirement of today, strength values have to reach 100% percent of the required value, while 95% percent are actually granted within the standardization process.

Bending classes C18, C24 (graded on its own and in combination with C35), C30, C30 without k_v, C35 and tension classes L17, L25 (graded on its own and in combination with L36), L30, L36 were analyzed. The country responsible for an increase in settings is identified.

Results and Discussion

What are the differences between the calculation methods for characteristic values? Settings are calculated for the strength class combinations specified above. For instance, the undivided (by regional aspects) tension dataset fulfills the requirements (MOR, MOE and density) for L36 at a setting of 12100 if the current calculation of characteristic values is applied (Table 3). For this strength class the MOR value is limiting the setting. The same is true for all other settings except for L25 where a setting of 10400 is required to reach the required MOE value of 10450 MPa. The calculated thresholds are used not only for the "*methods for the calculation of characteristic values"* but also for calculating *"costs for guaranteeing timber properties"*.

Table 3: Characteristic properties calculated according to EN 384 and yield for settings used for strength class combinations L36-L25-L17-reject (tension) and C35-C24-reject (bending).

grade	n total	MOR MPa	MOE MPa	density kg/m³	yield %	setting -				-
L36	1840	22.1	13300	410	44.3			IP	≥	12100
L25	1100	15.9	10500	376	26.5	12100	>	IP	≥	10400
L17	1110	11.0	8700	339	26.7	10400	>	IP	≥	7700
rej	106	-	-	-	2.6	7700	>	IP		
C35	699	35.1	15600	439	16.1			IP	≥	14200
C24	3308	21.4	10800	363	76.4	14200	>	IP	≥	8600
rej	324	-	-	-	7.5	8600	>	IP		

Differences between the calculation methods EN 384 and prEN 14358 are expected. The factors used in prEN 14358 to account for the variation within a timber sample lead to lower characteristic values. Depending on the in-grade variation and the deviation from the assumed lognormal distribution of a sample, lower or higher values characteristic values are expected in the first place.

The resulting characteristic MOR values for the chosen strength class combination are shown in Figure 2. While for the bending strength data, prEN 14358_lognormal leads to higher MOR values compared to EN 384 for all possible settings; this is not the case for tension strength data: almost no difference is found. The prEN 14358_lognormal calculation will not result in higher MOR values. While prEN 14358_ranking is in both cases only slightly below the value for the EN384, the prEN 14358_normal-method gives higher values for bending and far lower values for tension. Assuming the proposed normal distribution in prEN 14358, resulting tension MOR values are low compared to the other calculations. For bending data the spread for determined MOR values is lower. The reason for this cannot be gathered directly from the shown information. However, a small hint is hidden in Table 1.

The higher cov values for tension data remains in the graded samples. The relatively higher variation leads to lower characteristic strength values when a distribution is assumed for the calculation of characteristic values instead of using only the lower 5th percentile values, the ranking method is using.

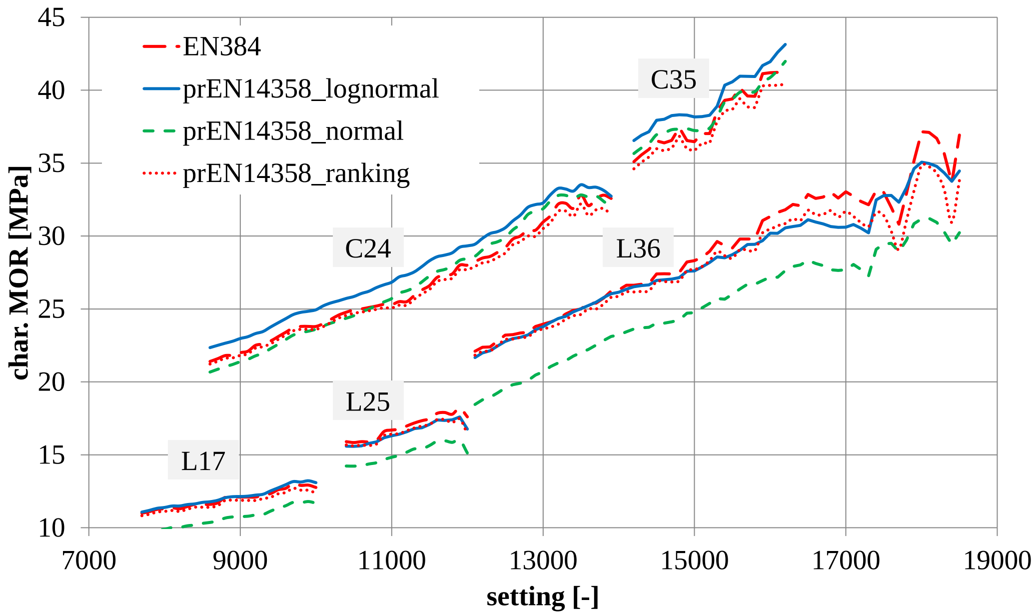

Figure 2: MOR values plotted against the settings for a strength class combination for bending and tension, respectively. A distinction is made between calculation according to EN 384 and prEN 14358.

Differences in results for the two calculations of MOE values are negligible (Figure 3). This is not further surprising as both methods use the average MOE as basic parameter for the calculation. prEN 14358 delivers slightly lower values as the variation within a grade is considered by adding a penalty factor.

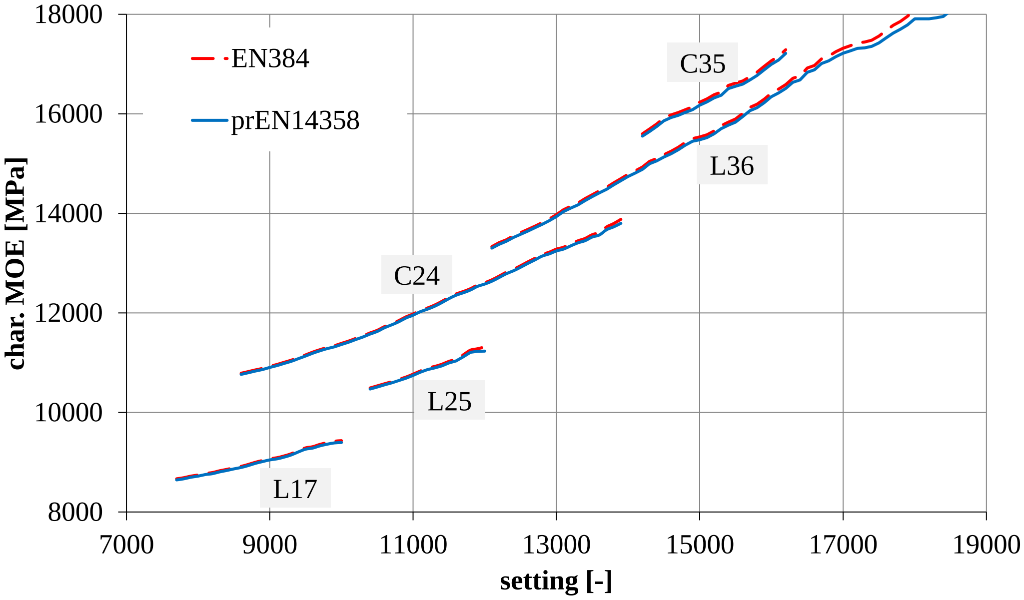

Figure 3: MOE values plotted against the settings for a strength class combination for bending and tension, respectively. A distinction is made between calculation according to EN 384 and prEN 14358.

For density values, the differences become larger again (Figure 4). Unlike for MOR, the characteristic density determined in accordance with prEN14358 results in lower values for both bending and tension. Even without using the density itself as a separate IP (which would further increase the quality of density prediction), assuming a normal distribution for density values of in-grade timber leads to lower 5th percentile values in all cases as expected. Although, differences for the particular settings are usually not above 10 kg/m³ this might be grade determining for spruce, especially for the density values listed in EN 338.

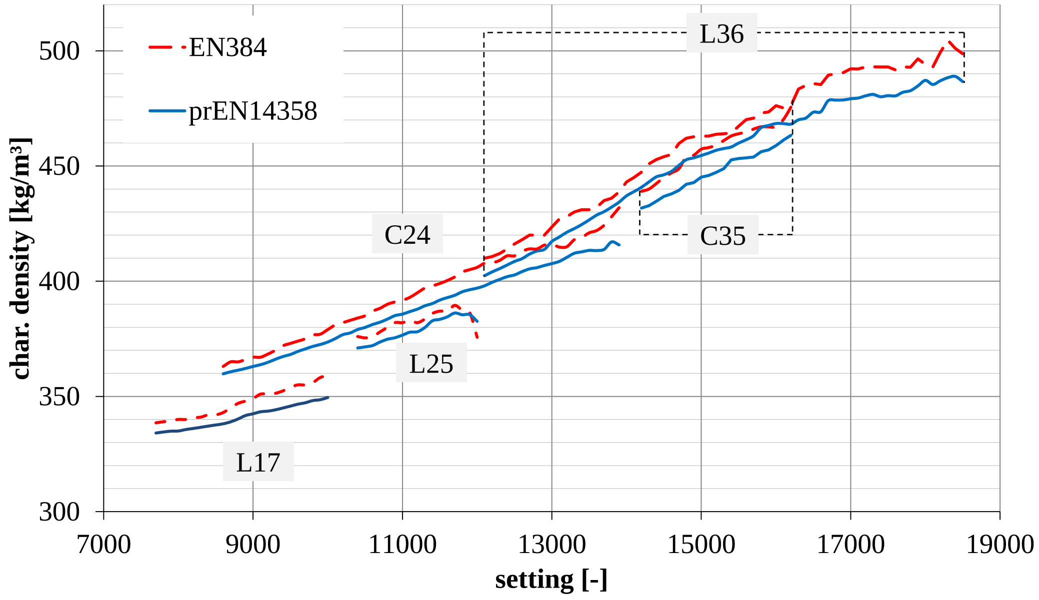

Figure 4: Density values plotted against the settings for a strength class combination for bending and tension, respectively. A distinction is made between calculation according to EN 384 and prEN 14358.

Which countries can form a grading area?

Table 4 shows the calculation results for bending data for equations 1 and 2. When all three threshold values are considered, some setting value leads to deviations from the European data. This is true for both, *RISK* and *LOSS* values. Hence, settings based on the complete data do not entirely match the population represented by the samples from single countries. Relative values of 0 or close to 0 mean, that for the country no problems for the country in terms of *RISK* or *LOSS* are expected if the settings are derived on the basis of the whole dataset. The MOR *RISK* value for AT sample shows that timber from that area will cause problems when characteristic values are checked on country basis. Otherwise, for timber from BE lower settings would be possible if MOR is grade determining. The high MOR *LOSS* values indicate that settings derived separately for BE would allow a higher yield. It can be found, that graded timber from AT, CZ, DE and SK shows too low characteristic MOR compared to Europe. The same is true for density and MOE in RO and UA. For AT the density values also appear to be too low. In order to judge the usefulness of this method, the results need to be compared to results from *Costs for guaranteeing timber properties*.

Table 4: Absolute (abs) and relative (rel) RISK and LOSS values for bending data separated for different countries using the EN 384 method.

Country	RISK						LOSS					
	MOR		MOE		DENS		MOR		MOE		DENS	
	abs	rel	abs	rel	abs	rel	abs	rel	abs	rel	abs	rel
	[MPa]	[-]	[MPa]	[-]	[kg/m³]	[-]	[MPa]	[-]	[MPa]	[-]	[kg/m³]	[-]
AT	-8.1	-0.41	-17	0.00	-22	-0.06	0.0	0.00	339	0.03	2.0	0.01
CZ	-2.8	-0.14	-28	0.00	-1	0.00	0.0	0.00	74	0.01	7.0	0.02
DE	-2.2	-0.11	-14	0.00	0	0.00	0.0	0.00	318	0.03	8.0	0.02
SK	-1.6	-0.08	-445	-0.04	-5	-0.01	0.9	0.05	59	0.01	1.0	0.00
FR	-0.7	-0.04	-349	-0.03	-7	-0.02	1.8	0.09	70	0.01	3.0	0.01
SE	-0.7	-0.04	0	0.00	0	0.00	0.5	0.03	309	0.03	5.0	0.01
PL	-0.6	-0.03	0	0.00	-1	0.00	0.3	0.02	227	0.02	6.0	0.02
RO	-0.3	-0.02	-1045	-0.09	-21	-0.06	1.3	0.07	0	0.00	0.0	0.00
SI	-0.2	-0.01	-90	-0.01	0	0.00	0.5	0.03	73	0.01	4.0	0.01
UA	-0.1	-0.01	-554	-0.05	-21	-0.06	1.4	0.07	0	0.00	0.0	0.00
BE	0.0	0.00	-463	-0.04	-1	0.00	3.2	0.16	0	0.00	7.0	0.02

Table 5 shows the calculation results for tension data for equations 1 and 2. The timber from CH that was tested over longer spans shows the expected negative *RISK* values for strength. Compared to the values for the bending data many countries show more extreme values for the MOE. Also for density more extreme *RISK* values can be found.

Tension and bending results are available only for some countries. They are not necessarily in line with one another. Thus, one might question the 0.6 ratio between tensile and bending strength (EN 338) for a particular country or representativeness of the samples. For some countries however, values correspond nicely. For instance, MOR *RISK* values for RO and UA are close to 0 while there MOE values are low.

Table 5: Absolute (abs) and relative (rel) RISK and LOSS values for tension data separated for different countries using the EN 384 method.

Country	RISK						LOSS					
	MOR		MOE		DENS		MOR		MOE		DENS	
	abs	rel	abs	rel	abs	rel	abs	rel	abs	rel	abs	rel
	[MPa]	[-]	[MPa]	[-]	[kg/m³]	[-]	[MPa]	[-]	[MPa]	[-]	[kg/m³]	[-]
CH	-4.1	-0.33	-117	-0.01	-1	0.00	0.0	0.00	30	0.00	1.0	0.00
PL	-2.5	-0.20	0	0.00	0	0.00	0.0	0.00	347	0.03	8.0	0.02
LV	-2.4	-0.19	-615	-0.06	0	0.00	0.1	0.01	13	0.00	8.0	0.02
AT	-1.1	-0.09	-763	-0.07	-1	0.00	0.3	0.02	2	0.00	3.0	0.01
CZ	-0.9	-0.07	-632	-0.06	-5	-0.01	0.7	0.06	0	0.00	2.0	0.01
SE	-0.8	-0.06	-1189	-0.11	-17	-0.05	0.6	0.05	0	0.00	0.0	0.00
UN	-0.2	-0.02	-760	-0.07	0	0.00	1.0	0.08	4	0.00	5.0	0.01
SI	-0.1	-0.01	0	0.00	-19	-0.05	1.9	0.15	627	0.06	0.0	0.00
RO	-0.1	-0.01	-525	-0.05	-43	-0.12	0.9	0.07	0	0.00	0.0	0.00
DE	-0.1	-0.01	0	0.00	0	0.00	0.5	0.04	470	0.04	8.0	0.02
SK	-0.1	-0.01	-251	-0.02	-28	-0.08	1.6	0.13	66	0.01	0.0	0.00
UA	-0.1	-0.01	-362	-0.03	-36	-0.10	1.0	0.08	3	0.00	0.0	0.00

What are the costs for guaranteeing timber properties on European, regional (Central Europe/ Eastern Europe) or country level? Several C- and L-classes were tested to find out about the effect on yield when timber properties are guaranteed on different levels. It is obvious, that timber properties in single countries will fail the requirements if the settings are derived based on the complete dataset. This is not surprising and is expected to happen for any two samples which are not similar enough. Table 6 gives an example for the popular grade C24 using EN 384 method. Whether obtained values per country are satisfying or not is not to be discussed here. Anyway, it is obvious that obtained characteristic values are below the requirements in several countries.

Table 6: Reached characteristic values and yield for single countries if the European settings (IP≥8100) for C24 are used (EN 384). Required MOR = 21.4 MPa, MOE = 10450 MPa, density = 350 kg/m³.

country [-]	MOR [MPa]	MOE [MPa]	density [kg/m³]	yield [%]
AT	19.3	12000	357	89.1
BE	24.2	11500	378	98.9
CZ	20.1	11500	376	97.4
DE	18.9	11400	359	90.1
FR	23.7	11900	376	99.1
PL	21.4	11600	368	97.0
RO	20.8	10000	341	89.9
SE	21.7	12000	370	96.2
SI	23.4	12000	380	98.9
SK	18.8	10500	359	93.7
UA	20.3	10600	341	94.3

What happens to the yield when the requirements have to be reached on regional or country level is presented graphically in Figure 5, Figure 6 and Figure 7. The yield is given for both methods of calculation, EN 384 and prEN 14358 including the following calculation methods: prEN 14358_lognormal for MOR, prEN 14358_non-parametric for MOE, and prEN 14358_normal for density (Table 2). The major separation in the figures is based on the grade or the grade within a grade combination. The reachable yield is shown below for at least 5 cases. On the very left, the yield can be found that results from settings that guarantee that the complete datasets reaches the requirements (“EU”). Moving right, the yield is connected to settings that work for different regions (“RE”). The region which leads to the required setting is mentioned below (CE Central Europe, EE Eastern Europe). Yields for settings that lead to safe timber properties on country level are given on third rank including the country which is crucial for the reduction. After the country that is responsible for the reduction is identified, it is excluded in the next step. Above the country code the number of countries for which the setting is valid can be found. The number and the source given are based on the EN 384 calculation method.

Figure 5 shows results for C-classes. While for C18 the yield does almost not react on the different proof level, it is different for C24. The difference between European and regional level is large. The required settings for EE lead to a decrease in yield of 6.5% for EN 384 method. For prEN 14358 the gap is clearly wider (14.2%). Density requirements lead to higher settings for EE. However, this could be easily avoided. Introducing an extra IP for the density would solve that problem. This in turn would result in higher yields (94.5% EN 384, 93.1% prEN 14358). Here, like for many other strength classes prEN 14358 usually leads to lower yields as the assumed normal distribution for density leads to lower characteristic density values (compare Figure 4). The same effect can be found for C30. The yield reduction for the EN 384-method is small as MOR is grade determining in this case. Using prEN 14358 density becomes decisive for timber from EE: For EN 384 the yield again is clearly lower when characteristic are guaranteed on country level. The low strength value for timber from AT causes a yield for the European data of only 32.9%. If guaranteed for the European data, the yield is much higher – it reaches 56.5%. For C30 not using k_v the difference between the proof of EU and RE is very small. For timber from AT no setting for C30 can be derived. Due to low MOR values for timber from DE and SE the yield drops. The same fact makes it impossible to derive settings for C35 for timber from AT, CZ and DE for EN 384. In contrast to C24 graded on its own, an additional IP for density would not help to avoid the drop in yield between as MOR is important in that case. Considering all tested strength classes no clear effect caused by the calculation method was found. Considering only EU prEN 14358 always results in higher yields.

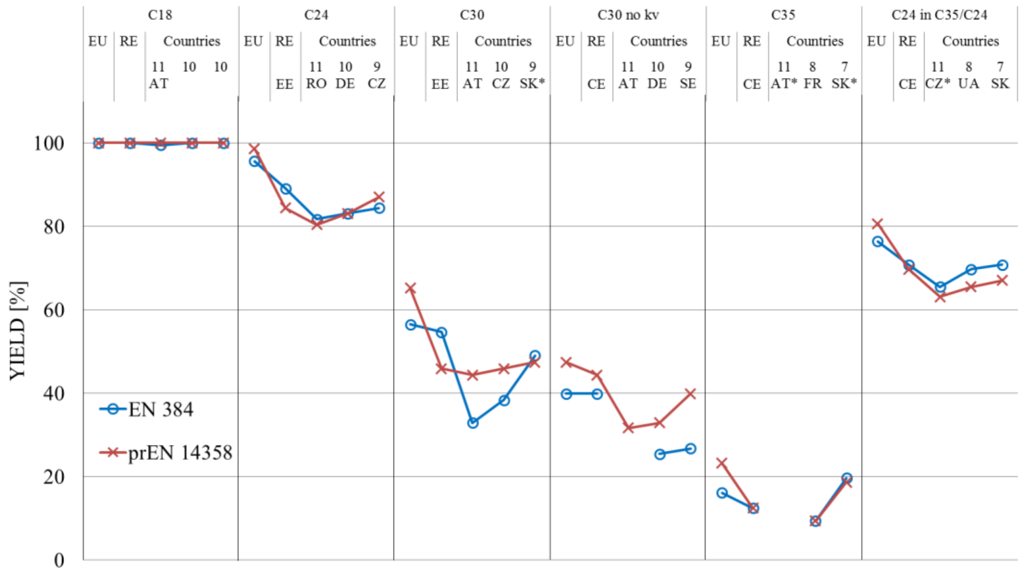

Figure 5: Yield for Europe for different C-classes depending on the source for that timber properties are guaranteed.

This observation is in clear contrast to the results for L-classes (Figure 6). Higher characteristic values result from calculations based on EN 384. Hence, yields are higher in this case. This is true independent of the zoom level. For timber from CH the lowest yields can be found across all strength classes. If a difference in yield is found between EU and RE this is always due to low density values of EE, except for L25 where the low MOE of EE timber is decisive. Even without the consideration of CH difference between the proof on EU and country level are immense. For all grades but for L25 from L25/L36 settings can be derived. Deviations occur for several countries. Raising the setting for L36 would help as more high strength pieces will be assigned to L25.

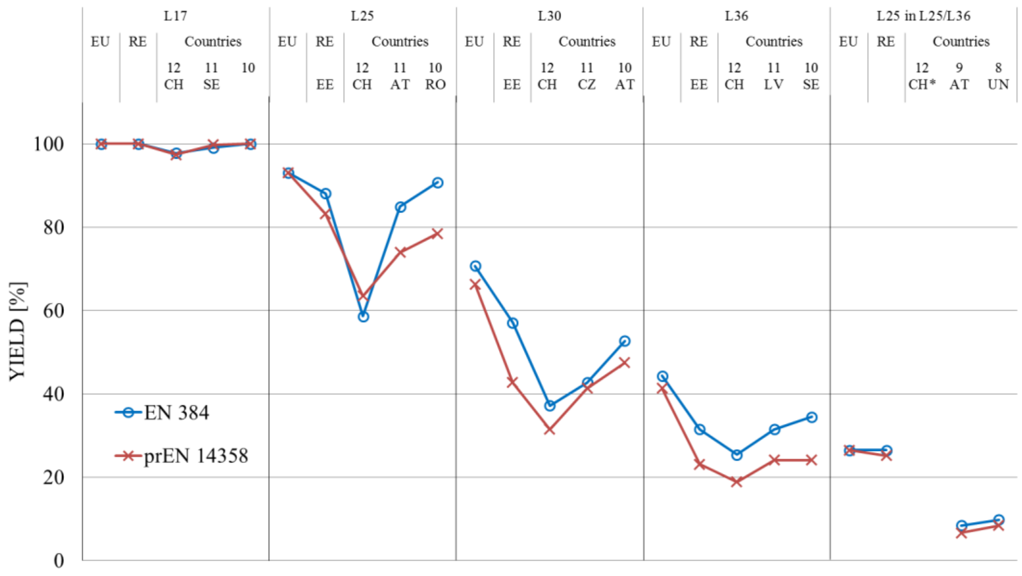

Figure 6: Yield for Europe for different L-classes depending on the source for that timber properties are guaranteed.

For two examples, C24 and L36, Figure 7 shows the yield for all analyzed countries. For C24 the calculation method has a minor effect. For BE, FR and SI no settings at all are necessary. All characteristic values can be reached without grading. The EU setting would lead to too low characteristics for timber from RO, DE, CZ, AT, UA and SK (EN 384). For these countries the settings derived on country basis lead to a lower yield. In L36 the yield is only lower if the settings are derived for CH, LV, SE or CZ or DE. For all other countries higher yields are reached. However, this is not true for the prEN 14358 method. There are only 3 countries for which the yield would be higher.

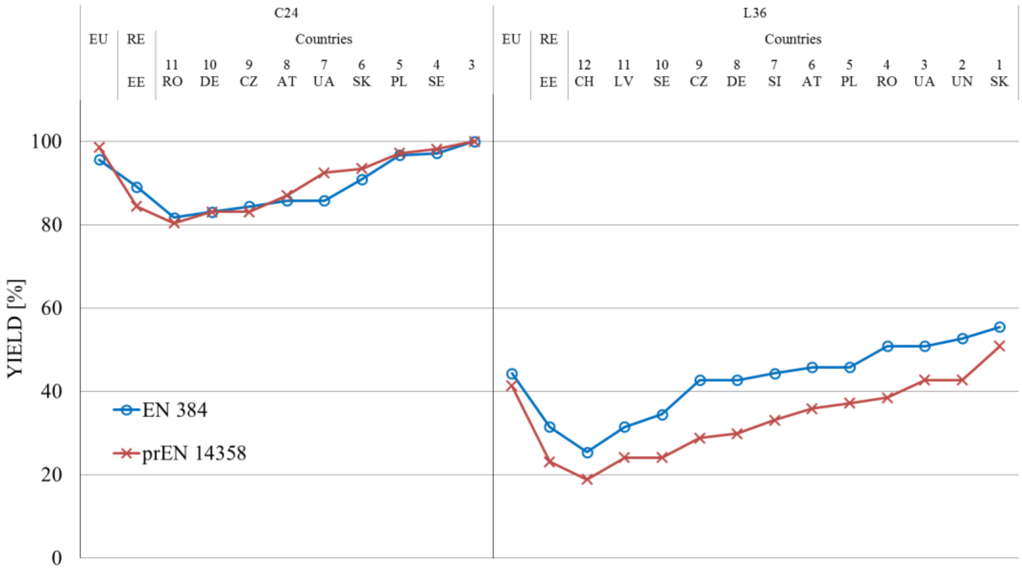

Figure 7: Yield for Europe for different stength classes depending on the source for that timber properties are guaranteed. All countries were analysed for C24 and L36.

Countries graded together vs. *Costs for guaranteeing timber properties*

The simple approach presented in the part "*Countries graded together"* allows identifying the countries which can cause problems in practical grading presented ("*Costs for guaranteeing timber properties*"). Countries with high RISK values are usually the countries which cause significant yield drops in several grades (compare Table 4 to Figure 5 and Table 5 to Figure 6). Depending on the species values single properties can be neglected if certain grade determining properties are way above the requirements of the class.

Conclusions

The proposed *calculation method* given in prEN14358 for characteristic values gives different results compared to the currently used method (EN384). Differences for MOE are small while MOR and density values can significantly differ.

The highest characteristic bending strength values result from assuming a log-normal distribution. This is at least true if the complete dataset is considered. For tension data the non-parametric method leads to the highest results. These results allow a prediction of the yield values. If prEN14358 became obligatory in future and the strength determines the class assignment higher yields can be expected for C-classes, lower yields for L-classes as in this case the coefficients of variation of in-grade timber are higher. Differences for the large ungraded dataset are small but can increase with decreasing sample sizes.

For the calculation of characteristic density values, the proposed normal distribution does not fit the real distribution if latest grading techniques are used. Dynamic MOE based grading machines usually measure the mass of the board anyway - allowing a more or less exact prediction of the density. The prediction of the density gets even stronger when a special indicating property for the density is used. This IP definitely leads to a truncated distribution of the density for the graded material. Using such a prediction method would even allow the prediction of a minimum instead of a 5th percentile value. This would make the discussion about how to calculate it obsolete.

A method, checking *countries* that can be *graded together*, was proposed. The method does not require an analysis for specific grades. The gained information can be used to identify countries for which similar timber characteristic for the graded timber can be expected. The loss in yield that can be expected due to high timber quality within a country is also considered. If for a certain species e.g. the density is much higher compared to the requirements in the strength classes it is possible, that only single properties need not to be considered. The method was compared to actual grading results. It was shown that the method is able to identify the critical countries.

Costs for guaranteeing timber properties on country level are high if countries are combined in one European grading area. Even on the basis of regions a considerable loss of yield has to be expected compared to the yield that can be expected for the European dataset. But a joint analysis of European grading data is not enough as results of characteristic values on country level show. However, sources with high quality timber also allow settings that are low compared to European ones.

The proposed method for grouping timber can help to identify origins for which equal settings can be used in a safe and economic way. If a geographical proximity is given in addition, a grading area is identified.

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ORIGINAL ARTICLE

Effects of grading procedures on the scatter of characteristic values of European grown sawn timber

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Abstract The natural scatter in mechanical properties of sawn timber must be reduced by grading the material either visually or mechanically. Depending on the grading procedure, the scatter of these properties varies. This study deals with their variation as influenced by the grading procedure. The effect of the grading principle is analyzed based on 4,893 sawn timber specimens from several European natural forests with widths up to 167 mm and depths up to 284 mm and using the method given in EN 14081-2:2010, CEN, Brussels (2010). Grading models for visual grading and machine grading are derived considering different source countries, strength classes and strength class combinations. Material safety factors for the graded material are then estimated in accordance with ISO 2394 (1998) to evaluate the grading outcomes. Analyzing and comparing the lower 5th-percentile to the requirements of EN 384: 2009, CEN, Brussels (2009), it is found that the actual strength for class C24 can be up to 20 % lower than required by the standard. This is true, regardless of whether the timber is graded visually or by an advanced grading machine using dynamic modulus of elasticity and knots. Low strength values can be expected especially in cases where a batch of timber is graded into a single strength class and reject only. High coefficients of variation of the graded material lead to the conclusion that high material safety factors are needed. On the contrary, if the material is graded by a machine and into more than two strength classes in one pass, it can be shown that the required material safety factors can be lower.

Keywords Visual grading · Machine grading · Growth areas · Test procedures · Material safety factor

1 Introduction

Timber for structural applications needs to be graded in order to guarantee minimum strength, stiffness and density values, as well as correctly derived material safety factors. Grading can be performed either visually using traditional visual grading rules, or by machine, using non-destructive measurements in order to predict the mechanical properties. In this paper, machine grading is based on dynamic modulus of elasticity and knots. Both grading procedures require an outcome that has a certain reliability, in order to justify the application of safety factors specified by design codes, such as Eurocode 5 [8] for timber structures.

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With increased volumes of timber traded between different European countries, grading operations are performed more and more on timber from different origins. In conjunction with this development, the amount of test data which can be used for grading (machine) approvals is increasing constantly. The available timber data can be used to obtain uniform settings covering large parts of Europe. The European standard for grading machine approval EN 14081-2 [9] was developed in times when much less data was available and is based on a proposal by Rouger [15]. In the meantime, some alternative methods for machine grading in Europe have been proposed by Sandomeer et al. [16], Ziethén and Bengtsson [19] and Ranta-Maunus [14], but so far none of these methods have been implemented. The current method has some problems with regard to the output, allowing large variations in actual strength, stiffness and density values depending on the machine settings for strength classes and strength class combinations.

This paper deals with the most common grading techniques and identifies methods of improvement. This analysis can be performed as today a dataset of 4,893 boards is available, covering many growth areas and a large range of quality and sizes from the north of Europe to the Ukraine.

The procedure for determining settings for a machine or boundaries for a visual grade requires the use of modification factors from a number of European standards, of which EN 384 [3] and EN 408 [4] are the most relevant as they prescribe specimen shapes and methods for statistical data analysis.

During the approval tests for a grading machine, timber quality, in terms of bending strength, modulus of elasticity and density, influences the initial (non-adjustable) settings. However, the machine settings are not only based on the weakest sample, but on a mean value of all sub-samples used in the approval procedure. As a consequence, the origin of the timber in the subsamples has an important influence on the assigned mechanical properties of the graded timber and on the settings. If the user of a grading machine uses timber from the same sources and in a similar proportion as used for the derivation of settings, the output material is assumed to reach the required strength, stiffness and density values. On the contrary, if a sawmill only uses timber from a limited region it can be shown that the results can be far from safe when the original approval testing covered a much larger area. If the incoming material is of low quality only, the graded material will regularly not meet the required values given in EN 384 [3].

Factors used in the derivation of machine settings and on strength or stiffness values are several, but a crucial factor for machine grading—k_v—will be discussed and analysed in detail.

The k_v factor is specified in EN 384 [3] and is to be applied on the characteristic strength value of the samples graded by a machine for strength classes up to C30 according to EN 338 [2]. The value of k_v is fixed at 1.12, independent of the quality of the machine or strength class combination. The idea behind this factor is that the variation of the strength values of sub-samples is smaller for machine graded timber as compared to visually graded timber. Applying k_v means that for the required 5th-percentile strength value, the visual grade shall arrive at the required value whereas machine graded timber may arrive at 0.89 of that value.

Similarly as k_v for strength, stiffness values (mean) may be lowered to 95 % if machine graded.

Another factor that influences the quality of visual and machine grading processes depends on the length of the pieces used in the analysis [10, 12, 13]. Other than the influence of the length of the pieces during the bending tests according to EN 384 [3] and EN 408 [4] pure length effects have not been taken into account here.

Samples of spruce with different origin have been graded both visually as well as by machine. A comparison is made between declared characteristic values and the actual characteristic values determined from bending test data. In addition an analysis is made about the required material factors (γ_M-values) for structural timber design on the basis of ISO 2394 [11]. As the quality of the grading process influences the scatter in material properties, a direct influence on the required safety factors can be shown on subsample level as well as for different grades and grade combinations.

Strength grading procedures in Europe were standardized decades ago when only few data from timber from Eastern Europe was available. The standards in force had been customized for relatively small datasets and growth areas. For these areas only minor variations of the natural scatter in mechanical properties were expected. The currently applied standards are re-evaluated in this paper, considering large datasets that have recently become available. Prescribed adjustment factors for machine grading and material safety factors for structural timber are analysed.

2 Material and method

2.1 Material

The dataset comprises a total of 4,893 specimens. The analysis is based on Norway spruce (*Picea abies*) originating from natural forests in Europe. As shown in Table 1, the spruce data covers many parts of Central, Northern and Eastern Europe. Sub-samples have been created according to geographical locations. The sampling was carried out in different regions within 11 different countries. This led to 10 sub-samples. It is assumed that the sampling is representative for the timber source from the respective region. The number of pieces in each sub-sample varies from 204 to 1,337 and the specific sample size (*N*) per region can be observed in Table 1. As the standard requires a minimum number of 100 pieces in a sub-sample, the amount of boards within each sub-sample is sufficient to derive settings according to the European standard EN 14081-2 [9]. The cross sections cover a wide range of structural sizes with thicknesses varying from 20 to 167 mm and the width (depth) from 63 to 284 mm. In terms of terminology, European practice does not differentiate between timber and lumber.

The variation in the number of pieces per subsample was tolerated as a result of grouping of subsamples based on the origin of the boards. While for Central and Eastern Europe enough data are available for this study, Northern European timber is underrepresented with only 210 boards from one area (South-Sweden), but this does not influence the outcomes.

Almost half of the dataset originates from the database of Holzforschung München: A total of 2,617 boards are mostly data of recent projects. The other part of the dataset contains 2,276 boards of the European “Gradewood”-Project.

2.2 Method

2.2.1 Nondestructive measurements

The non-destructive data used in the analysis have all been recorded at eight different European research institutes. Data such as density, eigenfrequency or the knot value have been measured under laboratory conditions. Round robin tests were carried out before the actual laboratory measurements at the different institutes to ensure reliable and comparable destructive and non-destructive test data.

Table 1 The dataset comprises timber from 10 geographical regions

Sub-sample	Region	*N*	MoR			MoE		ρ		MoE, dynamic		tKAR	
			Mean in N/mm^2	Cov in %	5 %	Mean in kN/mm^2	Cov in %	Mean in kg/m^3	Cov in %	Mean in kN/mm^2	Cov in %	Mean	Cov in %
A	Slovenia	1,126	43.4	30.7	22.5	11.2	20.5	445	9.9	12.8	19.4	0.25	39.9
B	Western Germany	1,337	42.2	32.2	21.2	11.5	20.3	435	10.5	12.3	17.9	0.24	42.5
C	North Germany	511	36.6	36.0	16.0	10.6	22.8	447	12.6	11.2	21.3	0.26	45.3
D	Austria Czech Rep.	298	36.7	35.5	16.9	10.5	25.3	440	13.2	12.3	23.7	0.31	44.3
E	Belgium	262	41.4	25.4	24.9	11.0	15.6	437	9.3	12.1	15.4	0.26	38.2
F	Luxembourg	209	40.0	27.1	22.7	10.7	16.1	434	9.1	11.9	16.2	0.26	38.8
G	Poland	433	38.5	31.4	20.9	10.8	20.6	440	10.8	11.7	20.4	0.32	31.9
H	Romania Slovakia	303	37.0	30.6	20.0	9.7	18.1	397	9.2	10.6	18.4	0.29	34.0
I	Sweden	210	42.5	35.2	19.5	10.7	21.8	435	11.9	12.0	20.9	0.22	44.3
J	Ukraine	204	36.2	29.4	19.4	9.6	18.7	389	9.5	10.5	18.8	0.28	36.4
	Total sample	4,893	40.6	32.4	20.2	10.9	21.0	435	11.2	12.0	20.1	0.26	41.4

Values for the total sample are calculated for the undivided dataset of all 4,893 specimens

Non-destructive data concerned tKAR (total Knot Area Ratio) and dynamic modulus of elasticity. The dynamic modulus of elasticity is calculated using the eigenfrequency, the density and the length. The tKAR is defined as the knot area within a maximum length of 150 mm projected on the end grain divided by the area of the cross section. Overlapping areas are only counted once.

2.2.2 *Destructive testing*

All destructive tests have been performed according to EN 408 [4] and the factors given in EN 384 [3] (k_h-factor, k_l-factor) have been applied. This means that all bending strength values have been adjusted to a reference depth of 150 mm and a reference test length of 18 times the depth. Whenever possible, the weakest section along the beam axis had to be placed between the loading points. The orientation of the board in edgewise bending tests was chosen randomly. Test values for the static bending modulus of elasticity not tested at the reference conditions were adjusted to 12 % moisture content by 2 % for every percentage point difference in moisture content.

Moisture content and density (ρ) measurements were carried out on small samples, free of defects and cut out close to failure location, using the oven dry method according to EN 13183-1 [5].

Table 1 gives the mean values and the coefficients of variation of the grade determining properties bending strength (MoR), static bending modulus of elasticity (MoE_{stat}) and density (ρ) as well as of the non-destructive parameters dynamic modulus of elasticity (MoE_{dyn}), and knot area ratio (tKAR). The 5th-percentile values of the bending strength and density have been determined by ranking, as the ranking method is required by the standard.

2.2.3 *Grading models*

Based on the total sample, two different models are calculated by means of (multiple) linear regression analysis. The first model contains only the tKAR-value and simulates visual grading. This can be compared to visual grading rules that predict the strength on the basis of knot size and knot location. The second model simulates machine grading. It contains the tKAR-value and additionally the dynamic modulus of elasticity (MoE_{dyn}). Equations (1) and (2) show the model values for the estimated bending strength $f_{m,est}$.

$$\text{model value visual grading } f_{m,est} = 58.2 - 67.4 * tKAR \quad (1)$$

$$\text{model value machine grading } f_{m,est} = 9.4 + 0.00334 * MoE_{dyn} - 34.4 * tKAR \quad (2)$$

The relationship between model value and actual bending strength is shown for both models in Figs. 1 and 2.

In order to ensure that the models based on tKAR-values are not worse than actually used visual grading standards, the model is compared with data from a region for which additional visual grading parameters were available for the specimens. Many visual grading rules are mainly based on the size of one knot. For example, the German visual grading standard DIN 4074-1 [1] uses a single knot value for specimens which are supposed to be used for edgewise bending applications. As can be seen from Figs. 3 and 4, the German single knot value would not lead to a more accurate grading result. The tKAR-value shows a slightly better coefficient of determination to strength in comparison to the usually used knot parameters in visual grading standards such as INSTA 142 or DIN 4074. In return, visual grading rules also contain other parameters for predicting the strength class, such as

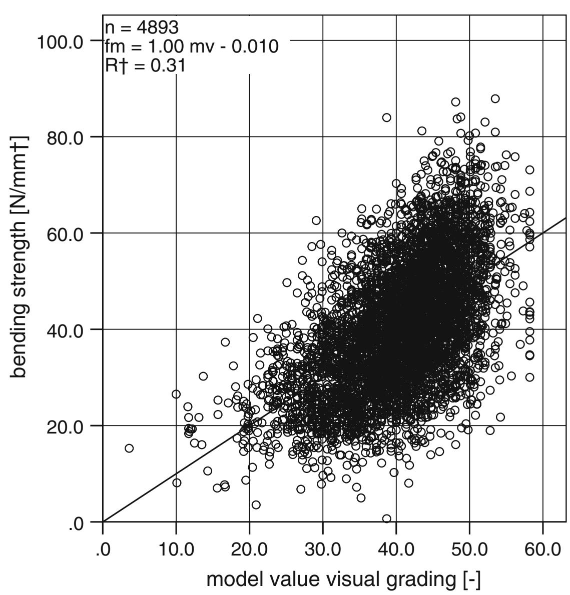

Fig. 1 The indicating property of the model for visual grading plotted against the bending strength

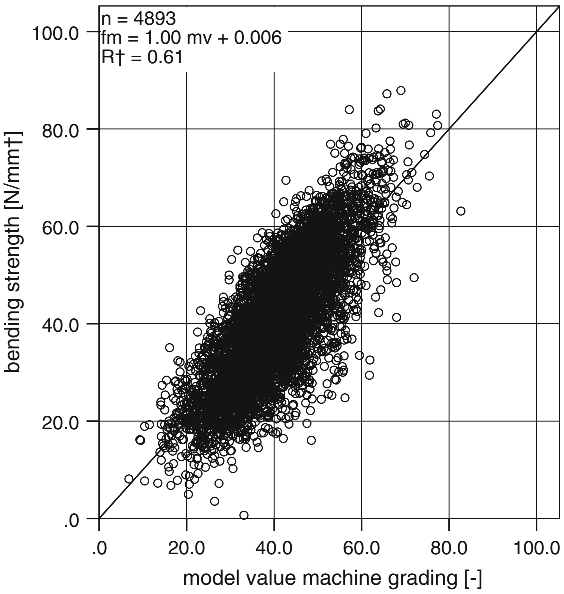

Fig. 2 The indicating property of the model for machine grading plotted against the bending strength

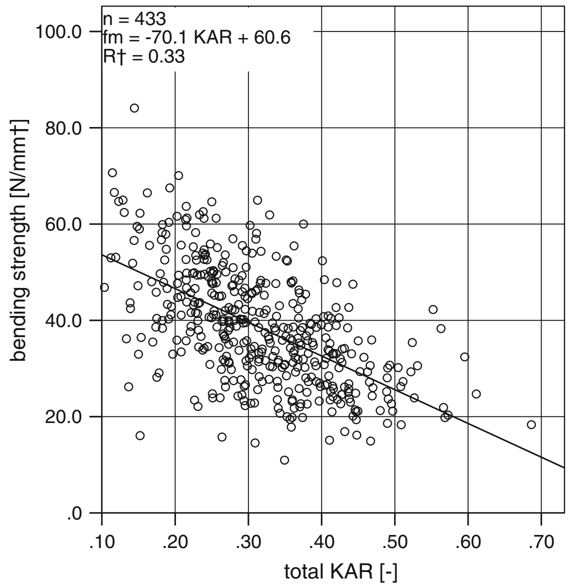

Fig. 3 Total KAR value plotted against the bending strength for subsample G

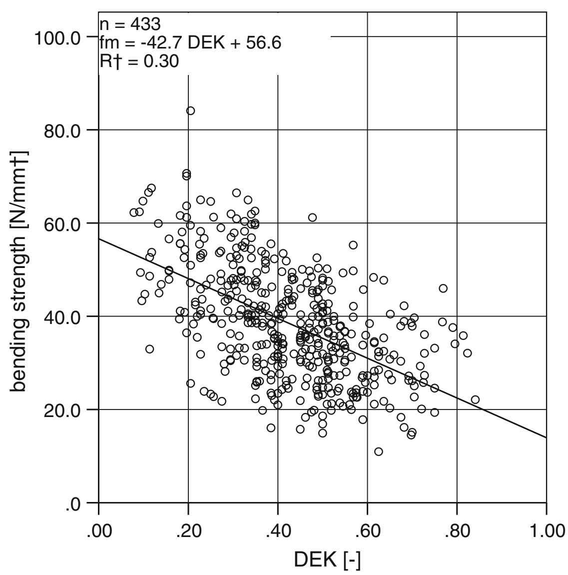

Fig. 4 Single knot value DEK (DIN 4074-1) plotted against the bending strength for subsample G

slope of grain, pith, rate of growth, fissures, wane, warp or compression wood. As a consequence, both methods have about the same accuracy with respect to the strength prediction. tKAR is considered representative for visual grading as an independent parameter.

2.2.4 Settings for model derivations

The required European C-classes requirements for strength, stiffness and density are shown in Table 2, taking into account the 95 % factor on mean bending modulus of elasticity given in EN 338 [2] and the k_v-factor on the characteristic bending strength as specified in EN 384 [3]. The characteristic density is determined by ranking. The influence of the k_v-factor used for reducing the strength requirements on the 5th-percentile level for strength classes C30 and below is given in the third column. If the k_v-factor is applied, the graded material is not expected to reach the required bending strength value given in EN 338 [2].

The settings have been derived for a so called "machine controlled system" in compliance with standard EN 14081-2 [9]. This method is denoted the "cost matrix method" [15]. The settings are derived maximising the yield of the highest grade to be graded, which means that for a strength class combination such as C35–C24-reject the yield of C35 is maximized before the settings for C24 are derived. For each sub-sample, the setting is determined from a sample comprising the remaining sub-samples ("excluded sub-sample method").

The optimum Grade (OG) provides the best possible assignment to a strength class of the tested boards.

Table 2 Required values of timber to be assigned in European C-classes according to EN 338 [2]

Grade	MoR (N/mm^2)	MoR/k_v (N/mm^2)	MoE_{mean} (N/mm^2)	0.95*MoE_{mean} (N/mm^2)	ρ_{12} (kg/m^3)
C40	40.0	40.0	14,000	13,300	420
C35	35.0	35.0	13,000	12,350	400
C30	30.0	26.8	12,000	11,400	380
C24	24.0	21.4	11,000	10,450	350
C18	18.0	16.1	9,000	8,550	320

These are assignments that would have been made possible by a fictitious perfect grading machine ($R^2 = 1$). All three properties (MoR, MoE, and ρ) should be optimized simultaneously according to algorithms from EN 14081-2 [9] and there are two possible calculation routines for optimum grades. The method applied here for the optimum grade is given in clause 6.2.4.5 of EN 14081-2 [9], note 2.

Settings are calculated for the following selected strength class combinations: C24-reject, C35–C24-reject, C30-reject, C35-reject and C40-reject. For strength classes equal or below C30, settings are calculated for different required strengths: strength values as given in EN 338 [2] and strength values divided by the k_v-factor.

The final analysis is done on sub-sample level.

2.2.5 *Method for the determination of material safety factors*

In order to find out whether the given safety factor for structural sawn timber in Eurocode 5 [8] is appropriate (advised γ_M value = 1.3, but may be specified on a national basis), the variation of the characteristic bending strength value of the sub-sample is studied. This is done in accordance with ISO 2394 [11], a standard partly influenced by the work of the JCSS [18]. A similar description for the derivation of a material safety factor can be found in—Eurocode—Basis of design [7]. The required safety factor γ_M is specified as follows:

$$\gamma_M = \eta \frac{R_k}{R_d} = \eta \frac{1 - kV_R}{1 - \alpha_R \beta V_R} \quad (3)$$

where R_k denotes 5th-percentile strength value from the test data; R_d is required design value; V_R is a coefficient of variation; η is a factor depending on the type of material and the test procedure; $k = 1.64$ for samples with a large number of specimens ($n \gg 30$); $\alpha_R = 3.8$ for normal structures with a reference period of 50 years; $\beta = 0.8$ for the governing load.

Equation (3) is rather sensitive for materials with high coefficients of variation (V_R) in combination with reliability index values (α_R) larger than 3.5. In most cases, the coefficient of variation of graded timber is larger than 0.25. The derived value of γ_M according to Eq. (3) includes the factor η, taking into account specific material effects, e.g. long term strength effects in materials like wood and concrete. In timber, the factor η can be taken as the modification factor k_{mod} for duration of load effects, generally having a value between 0.8 and 0.9, for the design governing loads such as wind and snow. The extreme values of these loads are normally of short or medium term, accumulated over the design life of the structure. As a consequence, the derived safety factors may be used as proposals for safety factors to be included directly in Eurocode 5 [8], but are especially useful to analyse any safety differences in batches of timber graded either visually or by machine. As such, they indicate the ratio that actual material factors in Eurocode 5 might have when a distinction between machine graded timber and visual graded timber is to be included. When used in conjunction with Eurocode 5, η ($\approx k_{mod}$) needs to be taken into account.

3 Results

3.1 Grading results

While all three grade determining properties have been considered and analysed, the results focus on the bending strength, as it proved to be the value closest to the limit values of the respective strength classes in most cases. Only in a few cases the values for modulus of elasticity and density of the graded timber were just below the requirements. The effect of k_v will be considered in more detail.

While C40 can only be graded by a machine and the use of the k_v-factor is not allowed in that case, a batch of timber graded as C24 is influenced by the grading method or the grade combination used. Results for C24 are presented in detail in Fig. 5 showing the extent to which the timber is influenced by the chosen grading procedure. Additionally, the frequency distributions for the ungraded material and the artificial optimum grade are shown. The dotted lines indicate the spread on the 5th-percentile level between the ungraded material and the highest strength value reached, when grading C24 in combination with C35. C24 graded on its own, using a machine applying the k_v-factor, leads to a strength distribution close to the ungraded material as can be seen from the cumulative frequency function. The lower distribution tails also allow a simple distinction between C24 graded on its own (visually or by machine) and in the grade combination C35–C24-reject. Differences between C24 graded by machine without k_v-factor and visual grading to C24 are negligible. This is also true for C24 graded in the strength class combination. Here, the k_v-factor has only little effect on the course of the frequency distribution.

Figures 6, 7, 8, 9, and 10 show the distributions for the different C24 grades for the lower 10 % tails. The results are shown for the 10 different subsamples. Every figure shows a continuous vertical black line giving the target strength value, namely 21.4 N/mm^2 when k_v is considered, 24.0 N/mm^2 if not. The two dotted lines show the range of the 5th-percentile value of the sub-samples.

Table 1 gives the range of the characteristic strength values for the ungraded subsamples. The characteristic strength values vary between 16.0 and 24.9 N/mm^2. An effective grading method should minimize these differences for each single grade. The optimum grade, which utilizes fully the possibilities of the procedure, leads to a maximum difference for C24 of 3.9 N/mm^2 between subsample H with 22.5 N/mm^2 and subsample E with 26.4 N/mm^2.

Figure 6 clearly shows lower characteristic strength values compared to the optimum grades. The minimum characteristic strength value is 18.9 N/mm^2 for subsample C, while the maximum of 24.9 N/mm^2 for subsample E is only slightly above the declared value. In Fig. 7, 8, 9, and 10 the same ranges are given for different grades and grade combinations, with the largest scatter in 5th-percentile values (20.9–27.7) for visual grading C24 in Fig. 8, and the smallest scatter

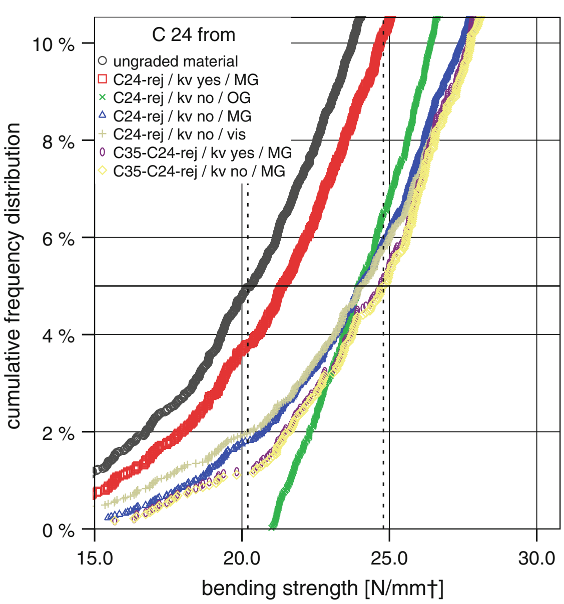

Fig. 5 Effect of the grading method on the graded material

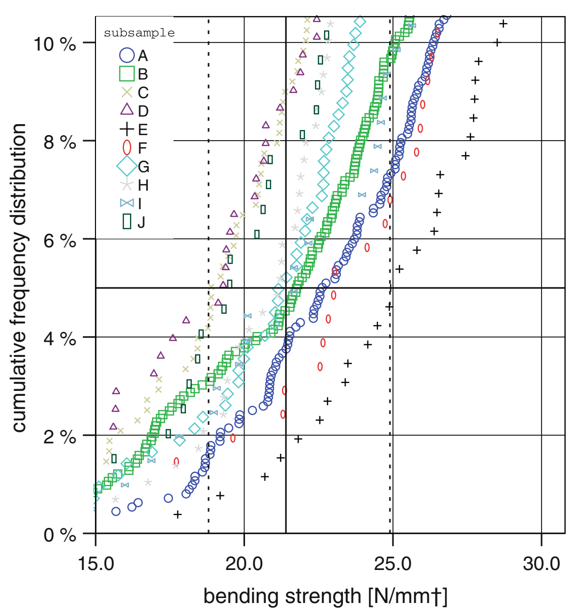

Fig. 6 C24 from C24-rej/kv—yes/MG—in-grade material analysed on subsample level

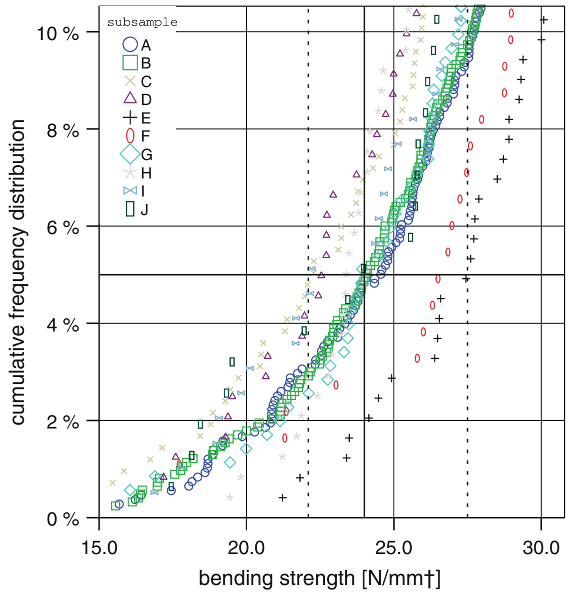

Fig. 7 C24 from C24-rej/kv—no/MG—in-grade material analysed on subsample level

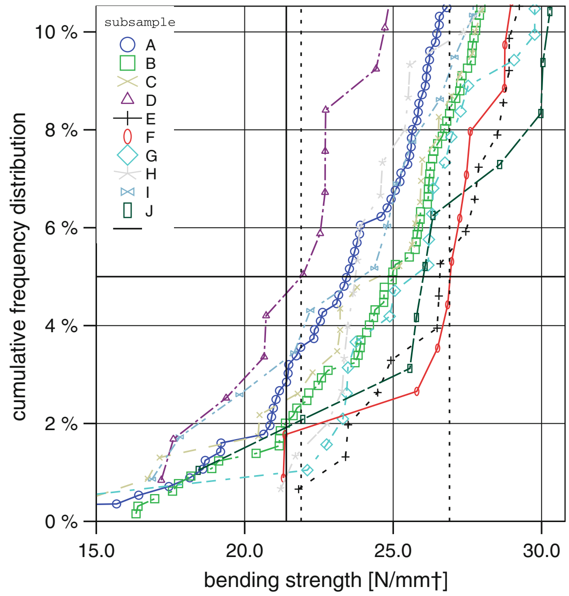

Fig. 9 C24 from C35-C24-rej/kv—yes/Visual—in-grade material analysed on subsample level

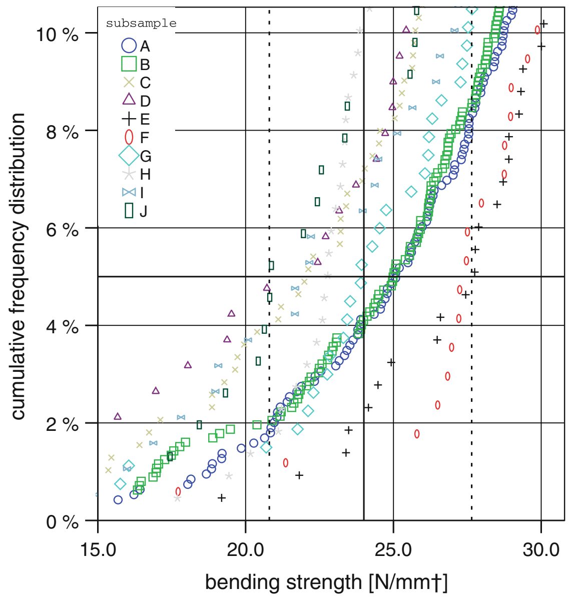

Fig. 8 C24 from C24-rej/kv—no/Visual—in-grade material analysed on subsample level

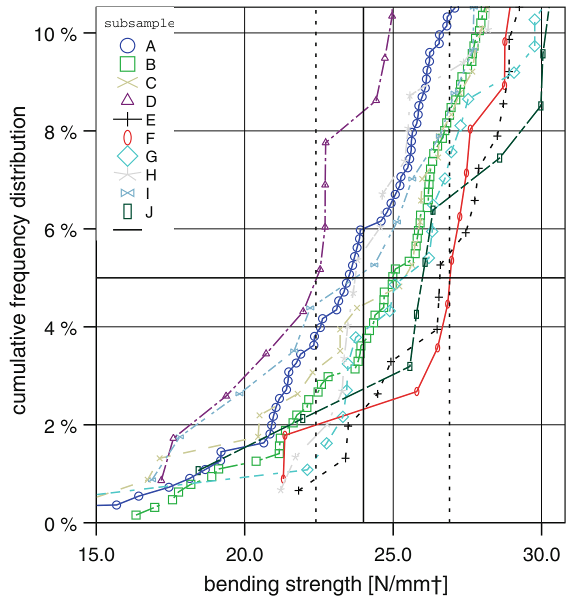

Fig. 10 C24 from C35-C24-rej/kv—no/Visual—in-grade material analysed on subsample level

(22.5–26.0) for machine grade combination C35–C24-reject in Fig. 10.

Table 3 shows the 5th-percentile strength values for the grades C30 and C24 for the total sample as well as for the different subsamples.

For C24 the yield reaches a maximum of 99 % for the undivided dataset in the optimum grade if the k_v-factor is used for the derivation of settings. A grading machine would assign almost the same amount of timber into C24 (98 %). The yield for visual grading drops to 79 %, but the scatter in strength values for the

Table 3 5th-percentile strength values

	Sub-sample					
Grade—C30						
Principle/grade		OG	OG	Machine	Machine	Visual
k_v		No	Yes	No	Yes	No
5th-percentile strength value (N/mm^2)	A	30.2	27.4	29.4	26.0	36.9
	B	30.3	27.4	31.2	27.8	33.3
	C	28.2	25.4	28.5	26.5	30.9
	D	30.1	25.9	25.8	23.3	–*
	E	30.5	28.0	31.9	27.8	–*
	F	29.4	27.0	32.6	28.0	–*
	G	30.5	26.9	31.6	27.8	–*
	H	29.6	26.3	34.4	24.5	–*
	I	28.8	26.6	27.7	25.3	20.4
	J	30.4	26.6	30.5	26.2	–*
	All	30.0	26.8	30.0	27.0	31.9
Yield	All	78 %	85 %	56 %	74 %	6 %
Grade—C24						
Principle/grade		OG	OG	Machine	Machine	Visual
k_v		No	Yes	No	Yes	No
5th-percentile strength value (N/mm^2)	A	25.3	23.1	24.5	22.6	25.1
	B	24.5	22.3	24.0	21.8	25.0
	C	23.3	20.0	22.3	18.9	22.0
	D	23.0	20.4	22.6	19.3	21.6
	E	26.4	24.5	27.5	24.9	27.7
	F	24.0	24.8	26.6	23.0	27.4
	G	23.2	21.4	23.9	21.2	23.9
	H	22.5	20.9	23.4	21.2	22.8
	I	24.6	21.3	22.2	21.7	21.9
	J	23.7	20.0	23.9	19.5	20.9
	All	24.0	21.4	24.0	21.4	24.0
Yield	All	94 %	99 %	89 %	98 %	79 %

For the single sub-samples divided by grades, grading principles and the use of the k_v factor. Characteristic strength (N/mm^2) and yield for the undivided sample

* Too few data available

single sub-samples is comparable to that of a grading machine.

For C30, the difference in yield between machine grading with and without k_v and visual grading increases. The assignment to C30 drops from 74 % (using k_v) to 56 % (without k_v), reaching a minimum of 6 % for visual grading. For visual grading, no 5th-percentile values are given in table for six sub-samples, as less than 10 specimens were available in these cases. The lowest values for machine graded timber can again be found in sub-sample D (25.8 and 23.3 N/mm^2).

For C24 and C30 comparing the optimum grade (OG) considering k_v to the optimum grade neglecting k_v, shows an offset of exactly 12 % ($k_v = 1.12$) for the undivided sample. However, when single sub-samples are compared this offset increases.

Where 30 N/mm^2 is required, sub-sample C has the lowest 5th-percentile strength value of all, namely 28.2 N/mm^2. This drops to a value of only 25.4 N/mm^2

when the k_v-factor is applied. For C24 similar effects can be observed.

3.2 Influence of the grading on the required γ_M values

In Table 4 the required γ_M values are given on the basis of Eq. (3). The given value is the average of the values of the individual sub-samples for each strength class. The scatter in terms of the standard deviation is also given.

For η a value of 0.85 is applied. This value is taken as the average value for k_{mod} for short and medium term loading in accordance with Eurocode 5 for Service Classes 1/2.

4 Discussion

One major problem of machine strength grading in accordance with EN 14081 and related standards is caused by the k_v-factor. The consequence of the k_v-factor is that target strength values for machine graded timber lie clearly below the declared value as indicated in Table 2. The grading requirements according to the current version of EN 14081 allows strength values which can additionally vary from this target value as the method does not require that each individual sub-sample meets the minimum strength requirements. Strength values for individual sub-samples can become as low as 23.3 N/mm^2 for C30 and 18.9 N/mm^2 for C24.

If k_v is not applied for machine grading, the 5th-percentile strength values obviously increase. In almost all cases the sub-sample strength values are even above the strength values for the optimum grade with k_v-factor included. Only for sub-sample D the value reaches 86 % of the required value for C30. In all other cases the values are at least 90 % of the required strength. While it is obvious that eliminating k_v leads to more reliable values, the aim of the paper is also to compare the reliability of machine grading with the simulated visual grading at the 5th-percentile strength level. This comparison can only be made for strength class C24, for which visual grading gives a yield of 79 %. The strength of visually graded C24 material is clearly above the values for machine graded timber if k_v is used. Compared to machine grading without k_v differences are becoming small when looking at the 5th-percentile values of the individual subsamples; the yield in visual grading is 10 % lower confirming the higher correlation between model value and bending strength for machines.

From the results of γ_M for strength class C24, it can be clearly seen that a positive effect of machine grading can only be obtained if C24 is graded in a grade combination with a higher grade. Otherwise, the characteristic strength of samples graded by a machine is not much better than when graded visually, neither is the coefficient of variation of the graded material influenced in a positive manner. The k_v-factor has a rather surprising effect on the 5th-percentile strength values of the subsamples. The required safety factor is higher for machine graded timber where settings are

Table 4 $\gamma_{M,mean}$ as the mean γ_M—value for the sub-samples

Grade	Grade class combination	k_v	Principle/grade	Yield	$\gamma_{M,Std}$ (ISO-2394)	$\gamma_{M,avg}$ (ISO-2394)
C24	C24-rej	No	OG	4,611	2.21	0.53
		No	Machine	4,338	2.22	0.85
		No	Visual	3,858	2.33	0.97
		Yes	Machine	4,773	3.36	1.50
	C35-C24-rej	No	Machine	2,339	1.45	0.15
		Yes	Machine	2,377	1.45	0.16
C30	C30-rej	No	Machine	2,720	1.49	0.31
		Yes	Machine	3,622	2.00	1.04
C35	C35-rej	No	Machine	1,391	1.28	0.19
C40	C40-rej	No	Machine	492	1.18	0.13

For different grades resulting from different grade class combinations using different grading principles and partly the k_v-factor derived including the k_v-factor. The reason for this is that by lowering the required value from 24 to $24/1.12 = 21.4$, a large number of test results with low strength are now included in the sample, increasing the coefficient of variation of the sub-sample. As a consequence, the k_v-factor as currently applied cannot be justified.

The results indicate further that visual grading of C30 is very difficult if not impossible. For several sub-samples it is not possible to calculate reliably 5th-percentile strength values due to the number of pieces in the grades per sub-sample. With a yield of only 6 % it seems as if visual grading in higher strength classes is not realistic.

The calculated values for γ_M show a clear dependency on the quality of the grading process. If the grading process allows for a clear separation of boards into more than two grades, the coefficient of variation is substantially reduced and consequently a lower value for γ_M could be declared. In the Finnish National Annex to Eurocode 5 [17], for strength classes of C35 and higher, a lower γ_M value may be applied, down from 1.4 to 1.25, or a 1.15 reduction. Looking at the results of Table 4, a γ_M-value of 1.3 for high quality machine graded timber can be justified for short and medium term loading. For visual graded timber, it is clear that without sufficient reduction in the coefficient of variation of the graded material, the current applied γ_M-values of 1.3 to 1.4 are optimistic. Additional means of quality control seem necessary, either during the grading operation by means of an output control system, or when the graded timber is used structurally.

For higher strength classes, machine grading shows a clear benefit in terms of lower required γ_M values. Also the scatter on sub-samples is smaller. If graded in a combination with class C35 or higher, a lower γ_M value can also be justified for C24 timber when compared to either visually graded C24 or machine graded ‘C24 and better’. The difference can be between 10 and 15 %.

5 Conclusions

Grading procedures have a clear effect on the strength, stiffness and density values of timber samples, originating from various natural forests around Europe. Visual grading into strength class C24 leads to a large scatter in 5th-percentile strength values for the different sub-samples. This in return would require high γ_M values. Visual grading of timber into strength class C30 seems not to be justifiable, certainly not for the application range (growth areas) given in EN 1912 [6]. The coefficient of variation of the 5th-percentile strength values is such that higher safety factors need to be applied than currently specified in Eurocode 5 [8]. In addition, in some sub-samples the yield is so low that no reliable 5th-percentile strength and density values can be determined.

When only C24 is graded, machine grading leads to a large variation in characteristic strength values within the grade (sub-sample level). When grading C24 by machine, a higher strength grade should be produced at the same time, increasing the threshold value for C24 and decreasing the variation within the grade. Grading of only one strength class by a machine should not be permitted, unless higher safety factors are prescribed for such material.

Adjustment factors given in EN 384 [3] and EN 14081-2 [9] intensify the problems caused by deriving settings for large growth areas according to the current standard. Therefore it is proposed to delete the k_v-factor from EN 384 [3] and EN 14081-2 [9]. The k_v-factor allows more test results from the low strength range to become part of the sub-sample, having a higher scatter and consequently requires higher safety factors. Apart from the fact that no evidence of its existence is found in the test results, there is a clear inconsistency in the standards. When deriving settings according to EN 14081-2 [9] the weakest sub-sample should be taken into account and limits on the allowable deviation from the target value should be specified.

The advantage of machine grading (i.e. more reliable material with smaller scatter in strength properties) should lead to the specification of different safety factors for visual and machine graded timber. For grades C30, C35 and C40 produced by a machine, there is clearly a much lower scatter at characteristic strength level, justifying a difference in safety factor between visual grading and machine grading. This could be done by specifying different γ_M values. Another option is the specification of a modification factor, taking into account the difference in variability between visual and machine grading.

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